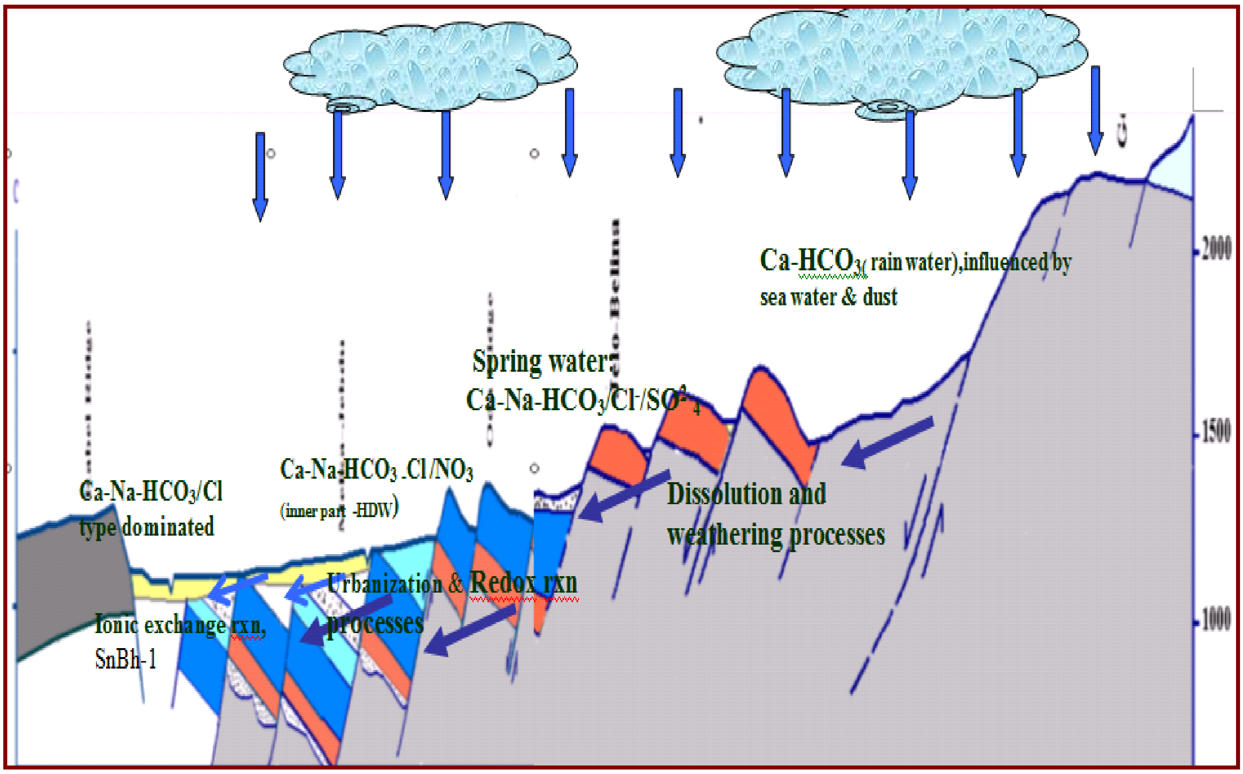
Master Thesis in Geosciences

Anthropogenic Impacts on Groundwater Resources in the urban Environment of Dire Dawa, Ethiopia

Eyilachew Y. Abate



UNIVERSITY OF OSLO
FACULTY OF MATHEMATICS AND NATURAL SCIENCES

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Discipline: Environmental Geology and Geosciences

Department of Geosciences

Faculty of Mathematics and Natural Sciences

UNIVERSITY OF OSLO

January 2010

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This work is published digitally through DUO – Digitale Utgivelser ved UiO

http://www.duo.uio.no

It is also catalogued in BIBSYS (http://www.bibsys.no/english)

Acknowledgements

I would like to express my gratitude to all those who contributed to this thesis. I want to thank my Advisers, Prof. Per Aagaard at the University of Oslo and Professor Gijs D. Breedveld (NGI) for their motivated and professional contribution. Further more I would like to acknowledge Prof. Per Aagaard in special way that advised and generously shared his experience and giving me reference books and software. His critical reading of the zero-draft master thesis and invaluable comments give the present shape of this thesis.

Many thanks to my wife Wubalem Demeke, for her love and assist a lot for the success of my study by cooking food and shopping stuffs. Thanks to everybody who in one way or the other contributed for all the valuable moral support and continuous encouragement during my study and the completion of my thesis work.

Oslo, January, 2010

Eyilachew Y. Abate

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Abstract

This study describes the contribution of anthropogenic factors for groundwater pollution in the urban environment of developing countries. Dire Dawa is one of the oldest urbanized and densely populated city in Ethiopia. The rapid urbanization and unplanned urban growth of Dire is manifested by the mismanagement of municipal wastes that clearly observed in every corner of the city. The groundwater quality shows more of nitrate and chloride caused by the direct influence of human activities. These untreated wastes (liquid & solid) contribute for groundwater pollution particularly in the phreatic aquifer. The municipal wastes and output of industrial activities have highly affected the urban environment since there is no proper treatment and enough urban facilities.

From the nature of contaminants and the complexity of hydrogeological settings, this study tried to incorporate and conceptualize the box model with contaminant transport in the phreatic aquifer to reflect the actual situations of Dire Dawa. From groundwater evolution of the basin we have clearly observed that the anthropogenic factors degraded the water quality by tracing the nitrate-chloride spatial trends. One of the most important sources for groundwater pollution is the release of septic effluent in phreatic aquifer which has a direct influence in the shallow wells. The concentration of nitrate becomes degraded in the downstream basin through hydrogeochemical processes by different mechanisms; ion exchange and biochemical denitrification process but still difficult to determine the degradation rate.

1. Introduction

1.1 Background

Water is a fundamental resource for socio-economic development & transformation; it is essential for maintaining healthy environment and ecosystems. There is a raising demand for fresh water resources as a result of increasing population and even by the advancement of technology; it has become difficult to treat the current context of growing pollution world-wide. This matter requires urgent attention, since water is scarce and such an important resource needs detailed scientific research all over the world in order to sustain and protect the water resource from pollution and for its wise utilization.

In many countries of the world groundwater is the only available natural resource for water supply and other activities. As a source of water supply groundwater has a number of essential advantages when compared with surface water. These advantages coupled with reduced groundwater vulnerability to pollution have resulted in wide groundwater usage for basic human needs, agricultural and industrial developments in the world. To meet the increasing demand of water due to rapid growth of population, urbanization and industrialization especially in developing countries, it is very important to evaluate groundwater resource qualitatively for future development plans of the region. Without fresh water of adequate quantity and quality, sustainable development will be impossible and life is in danger in the near future particularly in the south.

Urbanization is a challenging issue particularly in developing cities like Dire Dawa in Ethiopia due to groundwater pollution and aquifer vulnerability.The human intervention in the natural system has a significant effect on the quality of natural waters. Human activities like disposal of untreated toxic chemical and industrial waste into streams, unplanned urban development, lack of sewerage system, overpumping of aquifers, contamination of water bodies with substances that promote algal growth (possibly leading to eutrophication) and global warming are some of the prevailing causes of water quality degradation.

In the case of Dire Dawa area, groundwater is the only resource for water supply and industrial activities; as no surface water sources are available in the region. Keeping this vital resource is the primary issue for the sustainable development of the Dire Dawa town and its vicinity. The groundwater quality varies from place to place due to natural and human factors which depend on the nature of precipitation, geology, climate, biological, anthropogenic activities, and also hydrogeochemical processes. The hydrogeochmical evolution is also controlled by different mechanisms such as weathering processes, ion-exchange, redox reaction, biodegradation and other activities.

In the study area the geology is rather complex, which contribute to the natural modification of water quality in the upper part of the basin. The area is mostly covered by major geological complexes ranging from Precambrian rocks at higher elevations to the recent alluvial formation at the lower part of the basin (Seife, 1985). The presence of several salt lakes and proximity of Red Sea to the study area contribute for the change of water chemistry through evaporation-precipitation and water-rock interaction. Point and non-point sources of municipal wastes are major causes of groundwater pollution. The inputs of substances in the agriculture fields such a fertilizers, insecticides, and herbicides may pollute water sources and modified its quality. The water-rock interaction and its evolution play important role for the change of water chemistry in the groundwater system (Appelo, 2005).

The potential pollutant sources of in the Dire Dawa groundwater need more investigation in order to propose the possible remedial measures through scientific studies. The delineation of contaminant plumes is difficult because of the various potential emission sources. Thus, detection, quantification and remediation of contaminated sites in a city need more integrative approaches. This study helps to formulate environmental protection policy, effluent standards, the utilization of groundwater and the proper municipal waste management mechanisms. This study is also important to evaluate the future urban development plan for Dire Dawa city in particular and the region in general.

Several studies have been conducted related to geology and hydrogeology in the study area and its surroundings. The main gap here is to identify the pollutant sources (contaminated zone) and conceptualize the groundwater flow in relation with the contaminant transport towards the well-fields. Many factors may enhance the hydrochemical processes in the groundwater system. This study has tried to address and conceptualize the hydrogeodymanic system by applying different modeling techniques in order to identify pollutant sources, its fate and transport.

1.2. Objective

The general objective of this study is to identify the contaminated zone of aquifers in the Dire Dawa region by conceptualizing and assimilating the hydrogeochemical evolution of the Dire Dawa groundwater basin. This practice might help for effective and proper utilization of groundwater resource and environmental protection. It is also important for scientific work to exercise different modeling concepts by applying available data.

The specific objectives of the study include:

- ❖ To identify the different sources of pollutants and define the contaminant zone that influence the groundwater quality
- ❖ To evaluate the behavior of contaminants and mode of transport in groundwater system
- ❖ To conceptualize the fate and transport of contaminants in an unconfined aquifer based on the theoretical background and from practical field conditions
- ❖ To predict the possible influence area and travel time of the plumes towards the well-field

1.3 Methodology

In order to attain the above objectives the following methods used as shown in the simple conceptual flow chart model (Fig.1);

☞Review and analysis of available data or related studies:

- Study of previous works and literature on geological, hydrogeological and hydrochemistry of the area
- Tabulating water points ,evaluating water quality and accuracy of chemical analysis
- Visualizing hydrogeochemical data and geological settings of the study area

☞Conceptualize model:

- Schematically describe the hydrogeochemical processes and rainwater-soilwater-groundwater evolution
- Identifation of different water quality modifiers at different stages

☞ Conceptualize the box model to evaluate contaminant transport

- Assimilation and simulation of contaminant transport
- Analysis of results and discussion in connection with the contaminant in Dire Dawa aquifer

A simple conceptual flow chart model (Fig.1) of the methodology shows the systematic arrangement of the available data and conceptualizes the system by applying different hydraulic parameters

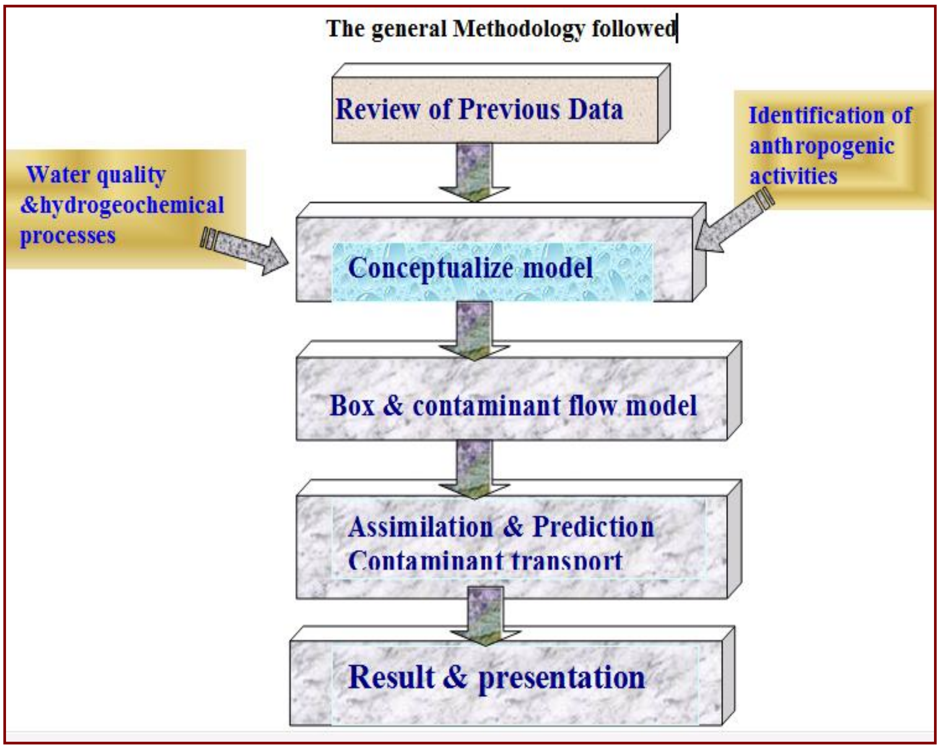

Fig.1 Simple conceptual flow of the general methodology

1.4 Previous works

Previously geological, hydrogeological, water quality the studies and other related works have been performed for different purpose in the Dire Dawa region. Most of studies have been conducted by the Federal sector organization of Addis Ababa and DDAC (Dire Dawa Adminstration council) in Dire Dawa i.e. Ministry of Water Resources (MoWR), Water Well Drilling Enterprise, Ethiopian Institute of Geological Survey (EIGS), Water Work Design and Supervision Enterprise (WWDSE), DDAC of Water Mines and Energy office and Hara water supply emergency project. These are the most important institutions working at the water sector in Ethiopia. The main hydrogeological work here was to plan and design water supply facilities for Dire Dawa and Harar towns as the ever increasing water demand far exceeded water supply. According to Minalah B. (2007), most of the previous works deal with specific issue but more comprehensive work was done by WWDSE (2004).

These studies have been conducted by those institutions for different purposes in the study area, which contribute a lot to achieve the above objectives of the research proposal. The data give enough background to conceptualize the situation and in order to identify the different sources of pollutants and to define the contaminant zone by applying different modeling techniques i.e box-model and application of GIS/ Surfer for analysis and presentation of the result.

2. General Overview of the study area

2.1 Location of Study Area

The project area is located in the East African Rift System within the Afar depression of Ethiopia. Afar depression is a region located in the horn of Africa at the junction of three major rift zones of the Earth's crust; the Ethiopian Rift, the Red Sea Rift and the Gulf of Aden. As it is shown in the map (Fig.2), the town is located within 250-300km radius from Red Sea and salt production lakes in the surrounding areas. The town was founded in 1902 by "chemen de fer Franco-Ethiopian" railroad, which was built by the French between the years 1897-1917. The railroad connected Addis Ababa- Dire Dawa to the port of Djibouti.

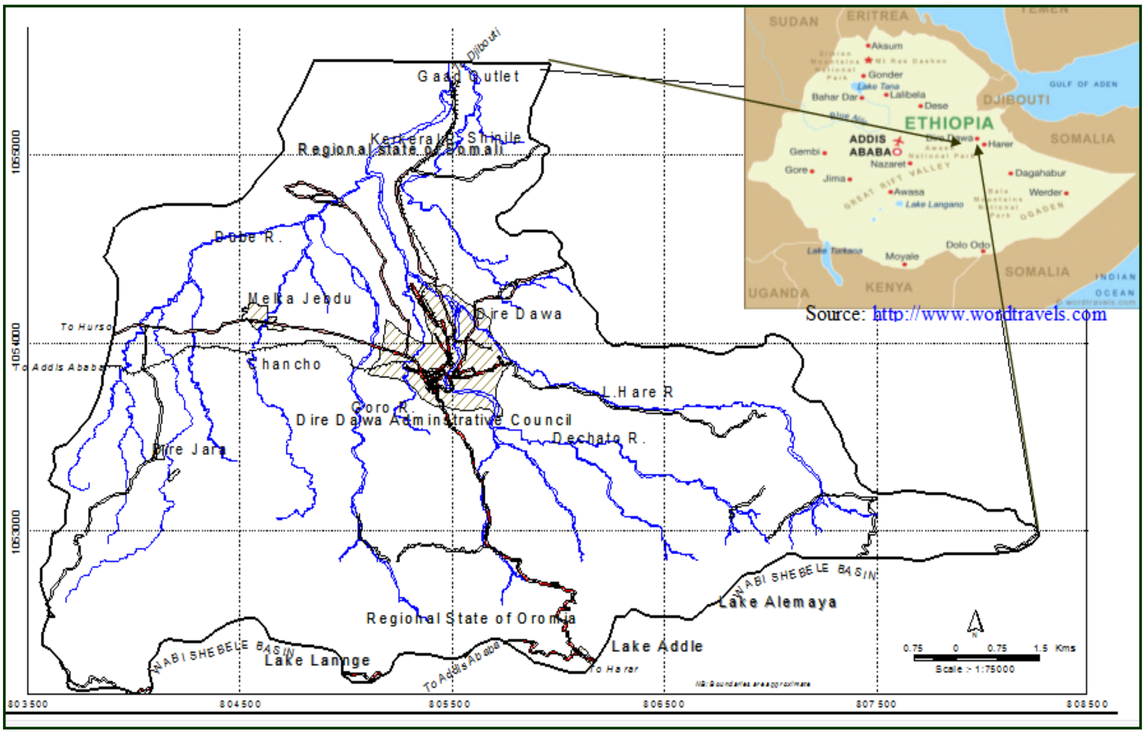

Fig.2 Location map of the study area (modified from WWDSE, 2004)

Dire Dawa is the second largest and oldest urbanized centre in Ethiopia, next to Addis Ababa. According to Central Statistic Authority CSA (2005) projection the total population of Dire Dawa by the year 2009 has estimated about 398,000. It has an enormous development potential, industries mainly comprise food-processing plants, textile and cement factory. The groundwater is the main source of water in the region, but it is highly exploited and depleted due to excessive pumping rate of about 400l/s for urban activity purposes (WWDSE, 2003). There are many private shallow and deep wells in the city also.

2.2 Physiography and Drainage

The physiography of the area is mainly controlled by volcano-tectonic related activities. The area is characterized by successive short running E-W oriented step faults forming half graben and horsts. The aggregated throw of the fault made the area to drop its elevation from more than 2200m at Dhangago to below 1000m at the north part of Shinile town (Fig.3). The Satellite image profile shows how the elevations drop from south to north direction. The geomorphology of the study area can be classified into three major features: the escarpment, the transitional region and the alluvial plains (WWDSE, 2004). There is an altitude difference of about 1120 m between the alluvial plain and the mountain peaks of the escarpment over a distance of 13,300 m.

The transitional areas are mainly characterised by small outcrops of sedimentary rocks, basalts and some recent coarse alluvial sediments. In this area the topography is gentle and the bed rocks are close to the surface. The alluvial plains are characterised by a gentle to flat topography. Except for some volcanic hills of younger age, the Mesozoic and the Tertiary rocks are buried deep inside the sediments in the lower basin (refer. the geological cross-section and stratigraphy, Annex-IV).

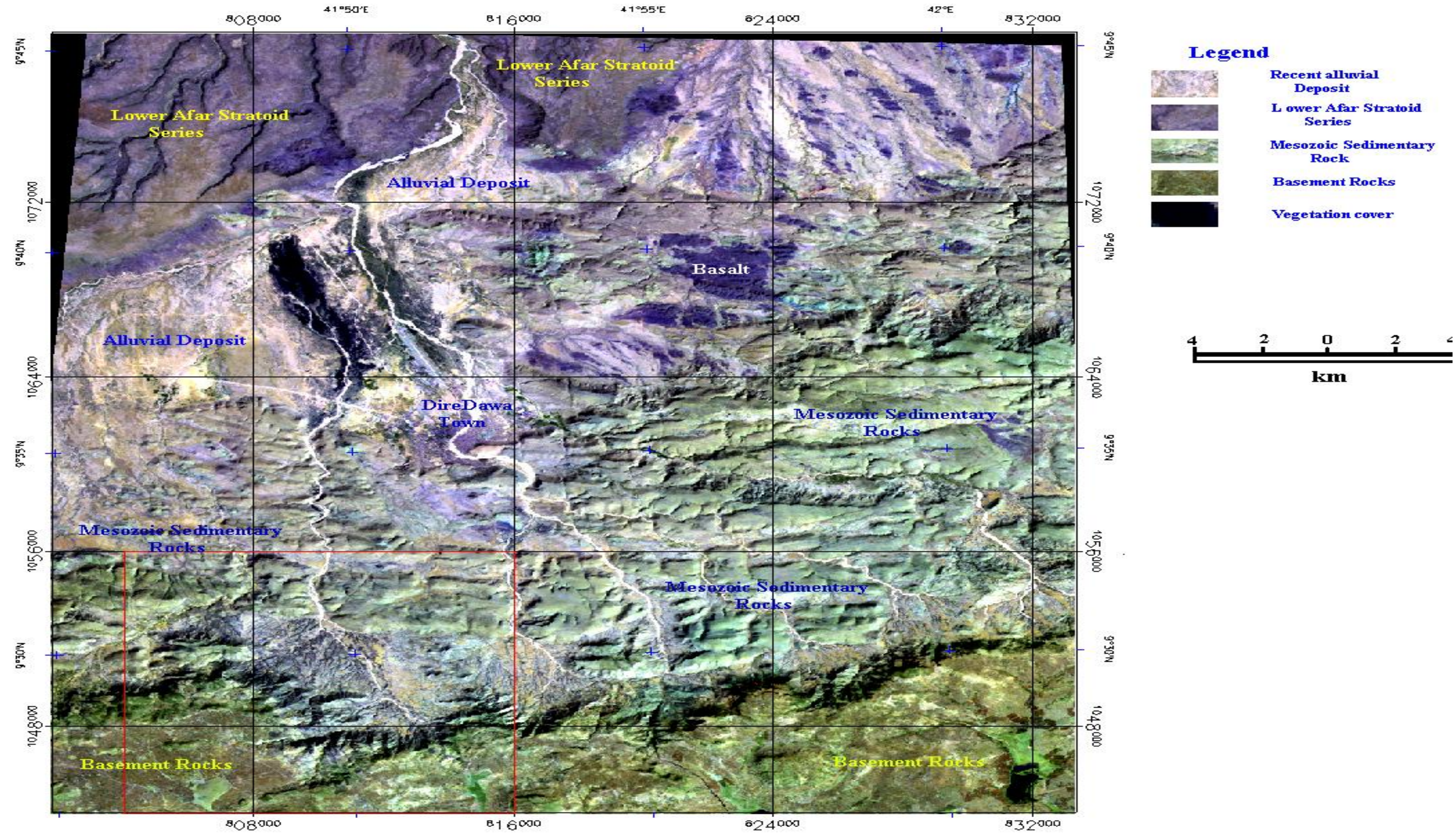

Fig.3 Satellite image enhanced (E-W) filtered and geological tonal variation (modified after Mirus, 2003)

As we can observe from Fig.4, most of the drainage patterns are South-North direction. Most of seasonal streams begin from the basin divider of Wabi Shebele-Awash River basin and flow towards the Dire Dawa plain areas. Springs originated from the escarpment zone of the catchment area, mostly within the Mesozoic sedimentary terrain. More than 100 deep bore holes and hand dug wells are located in the down stream (Fig.4) in the Dire Dawa town and its vicinity.

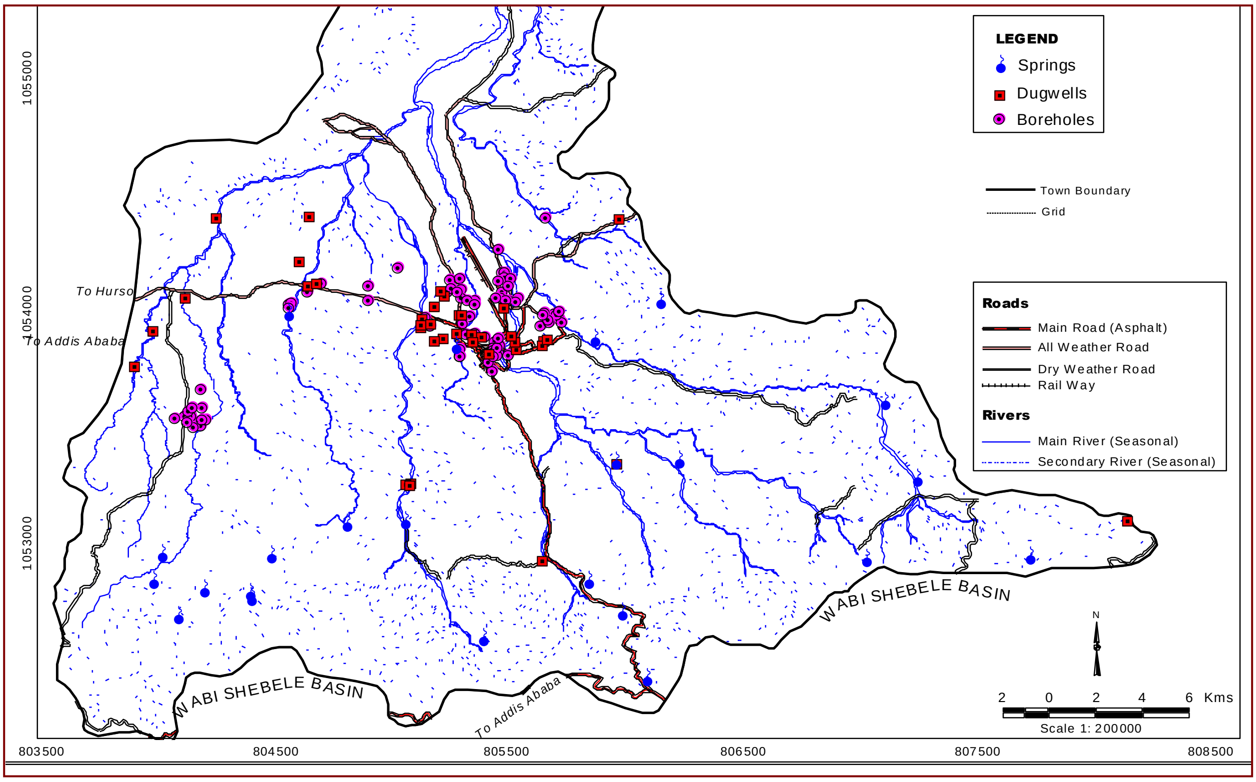

Fig.4 Water points and drainage system in the Dire Dawa Basin (WWDSE, E. Abate, MoWR, 2004)

2.3 Climate and Hydrology

The study area is generally characterized by arid or semi-arid climate. Based on the National Meteorological Service data of Dire Dawa(1972-2002), the mean (min.-max.) annual temperature of Dire-Dawa town varies from 19^{0}C to 35^{0}C (annex-II). The annual precipitation varies from 440.8 mm to 855.2mm with mean precipitation of 618mm. Since Dire Dawa is located in the arid and semi-arid zone, the potential evapotaranspiration (PET) is higher than the actual evapotranspriration (AET) in the area (Fig.5) by applying THORNTHWAITE & MATHER method. The town is situated at 1160 meter above sea level. There is no any perennial stream/river except intermittent-flashing streams along the Dechato channel.

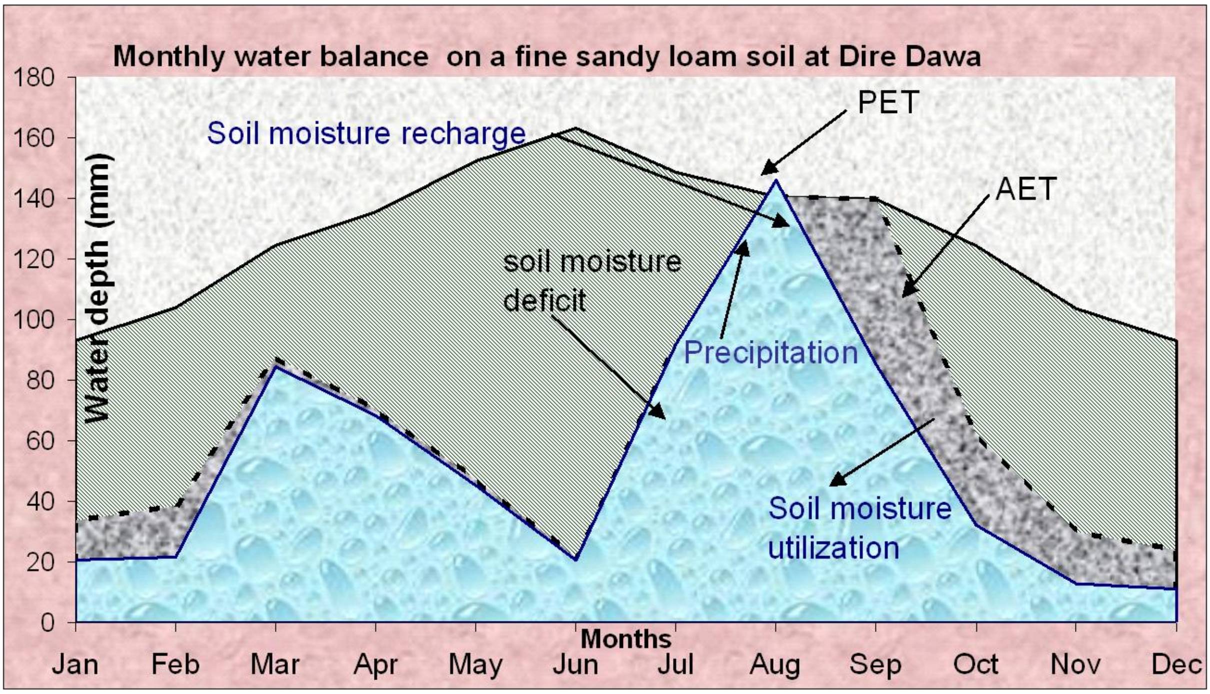

Fig.5 Monthly water balance on a fine sandy soil at Dire Dawa

2.4 Water Supply and Sanitation

The main source of water for domestic supply is groundwater from Sabiyan well-field located within the city expansion and scatter settlement part at the northwestern periphery of the Dire Dawa. Groundwater is the only water source in the Dire Dawa region. At present almost 100% water supply for domestic, industrial and irrigation purposes come from bore holes, hand-dug wells and springs for city and surrounding rural population. According to WWDSE (2004) preliminary estimation of the groundwater recharge is about 300-370 l/s, but the actual abstraction is more than this figure which includes the private bore holes.

The poor sanitation condition together with the lack of proper waste disposal mechanisms attributed to severely effect of pollution of both surface (seasonal) and ground water resources of the area. The most serious effect of pollution was observed in shallow wells, which is the reflection of all anthropogenic impact in the groundwater bodies. Taye A. (1988) report stated that Dire Dawa town is a fast growing industrial and commercial town, which produces pollutants in great quantities. The town has no sewer system and wastewater treatment plant. The main sources of pollution are multiple point sources pollution of pit latrines, septic tanks and linear source pollution of industrial and domestic waste disposal along the sandy seasonal river channels.

Human waste disposals are simply released to the pit latrines and septic tanks which have a chance for the rapid infiltration condition in the unsaturated zone of the sandy alluvial formation of the area. It is estimated that annually about 65,000 tons of human excreta is simply disposed and about 10,000 m^3 of solid wastes is dumped within the surrounding areas (WWDSE, 2004).

Waste generated from industries, agricultural activities, households, market centers, institutions, garages, fuel stations and the health centers are the main sources of pollutants that may affect the quality of water in the area. As a result, over 75 % of the health problems in Ethiopia are due to transmittable diseases attributed to unsafe and inadequate water supply; particularly human waste disposal system. Apart from its direct effect on the hydrogeologic system as pollutant through percolation, it may create favorable conditions for the reproduction vector causing disease.

As to the (DDAC,2000) conservation strategy document, the solid waste collection and disposal situation in Dire Dawa is 76% dump outside in an open field, 14% in pit, and 10% burning. But the main challenge is that all the waste components (solid and liquid wastes) are disposed at the zone of groundwater potential areas and may easily contaminate the water sources. Waste disposal sites are on pheartic aquifer, not selected according to hydrogeological settings. The main solid waste disposal area is the sandy dry stream channel of Dechatu River channel that divides the town into two almost equal parts. Solid waste heap is clearly seen in the dry river channel starting from the upper part of the city (Addis Ketema) to the lower part.

According to the information from the Health Office of the DDAC (2000), the present practice of sullage (grey water) disposal in the city is latrine (12%), road-channel (6%), open field (78%) and other (septic tank, 4%). There are reports and water sample results that show water quality problems in the Dire Dawa region. Nitrate and calcium (hardness) content in the town's water source is a serious concern (Ketema , 1982). The people have settled close to some of the wells (i.e. Sabiayan, Legehare and Megala areas) and release wastes in the surrounding of the well field which is potentially contaminating the ground water (Taye, 1988). According to the regional conservation strategy document of 2000, the ten top diseases common in the administration are shown in the table.1 below. Many of the diseases which have been reported can be linked to the inadequacy of sanitation and water supply.

Table.1 Top ten diseases in Dire Dawa, DDAC, 1999/ 2000

Types of disease	Patients	
	Number	Percent
AURTI	4524	17.5
AFI	4522	17.5
Tuberculosis	3417	13.2
Pneumonia	3001	11.6
Gastro-Duodenitis	2464	9.5
Skin and subcutaneous infection	2007	7.8
Malaria	1975	7.6
Homicide and Injury	1343	5.1
UTI	1318	5.1
Bacillary Dysentery	1297	5.0

Source: Dire Dawa Dil Chora Hospital out patient department

- ***URTI-Upper Respiratory Tract Infections** are the illnesses caused by an acute infection which involves the upper respiratory tract,*
- **__AFI__-from the Latin word febris, meaning fever, an Acute Febrile Illness is a type of illness characterized by a sudden onset of fever, which is an increase in internal body temperature to levels above normal,*

***UTI- Urinary Tract Infection-** is a bacterial infection that affects any part of the urinary tract.*

It is noted that dysentery and malaria are the second and the third causes of death in the region which are caused by water and sanitation activities. From the general assessment and overview, the main cause of death is highly connected to the living standard (poverty) with water, sanitation and environment.

3. Hydrogeological Settings and Anthropogenic Activities

3.1. Geologic and Stratigaphy profile

Geologically, the study area comprises of Precambrian with high grade metamorphic rocks (gneiss, pegmatite and granodiorite), Jurassic Adigrat sandstone and Hamaliei limestone with varies thicknesses and compositions which are located in the upper most part of the area. Cretaceous upper sandstone and Tertiary basalts outcrops have observed in the transitional part of the area (Mirus, 2003). The geological events and stratigraphy of the area are shown in the table.2 below. The downstream area is dominantly covered by alluvial sediment deposits as it observed on (Fig.6).The upper sandstone and Hamanlei limestone units are the most productive aquifers in the area (Tesfamichael, 1974). Geological structures; faults, fracturing and degree of karstification are the determining factors for occurrence of groundwater and flow regime as shown at the regional geological map (Fig.6).

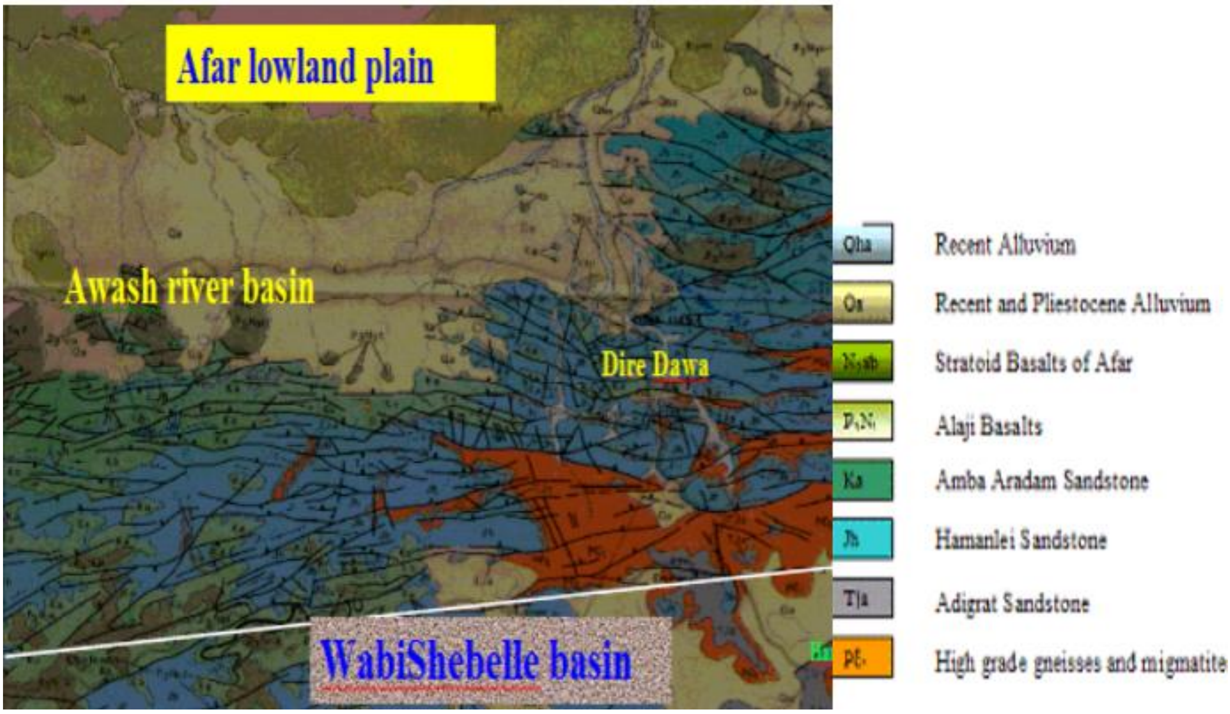

Fig.6 Regional geological map of Dire Dawa and Harer Region (EIGS 1986)

According to Mesfin (1981) the geological formation and hydrogeological conditions of the area is a function of geomorphological settings. Outcrops of Precambrian rocks, Adigrat sandstone, Hamanalei limestone, upper sandstone and basalts mostly covered the escarpment while the down thrown plain is dominantly covered by alluvial deposits. Both the plains and the escarpment are highly dissected by east-west trending faults as it observed from (Fig.7).

Based on stratigraphy and tectonic activities, the Dire Dawa area can be classified in to four main geological units (WWDSE, 2004) and the geological events are summarized in (table.2).These units are:

a. Basement complex rocks: composed of gneiss, pegmatite and granodiorite of metamorphic rocks which covered in the upper part of the Dire Dawa Basin. Fractured and weathered part of this formation may have very little water. Practically it is impervious.
b. Mesozoic sediments (lower & upper sandstones and the limestone unite): This formation mainly located in the transitional zone and the potential aquifer of the study area.
   - Jurassic Adigrat sandstones un-conformably overlie the basement complex with a thickness of not more than 20 meters, fractured and pervious formation.
   - Jurassic Hamanlei limestone (middle) varies in thickness up to 200 meters and its lower part is interbeded with shales overlain with oolitic limestone. This formation together with upper sandstone makes the main water-bearing horizon in the area.
   - Cretaceous Amba-aradam sandstones: composed of quartzose sand stone, thickness from 150 to 200 meters at some places interbeded with basaltic flows (lava flows within the sediments or sills) and limestone intercalations. This formation is the main water-bearing horizon in the area.
c. Tertiary volcanoes: Alaji formation (Acidic, lower trap basalts) predominantly basalts and Afar Stratoid Basalts. The Alaji formation overlies on the upper sandstone un-conformably. It has a wide spread area coverage and is practically impervious.
d. Quaternary formation: All rivers and streams descending from the escarpment have built large areas extended and thick alluvial deposits. These deposits consist of cobbles and coarse-grained sediments near the escarpment, while they consist of fine detrital sediments in the plain area. The alluvial sediment is one of the water bearing formation in the area.

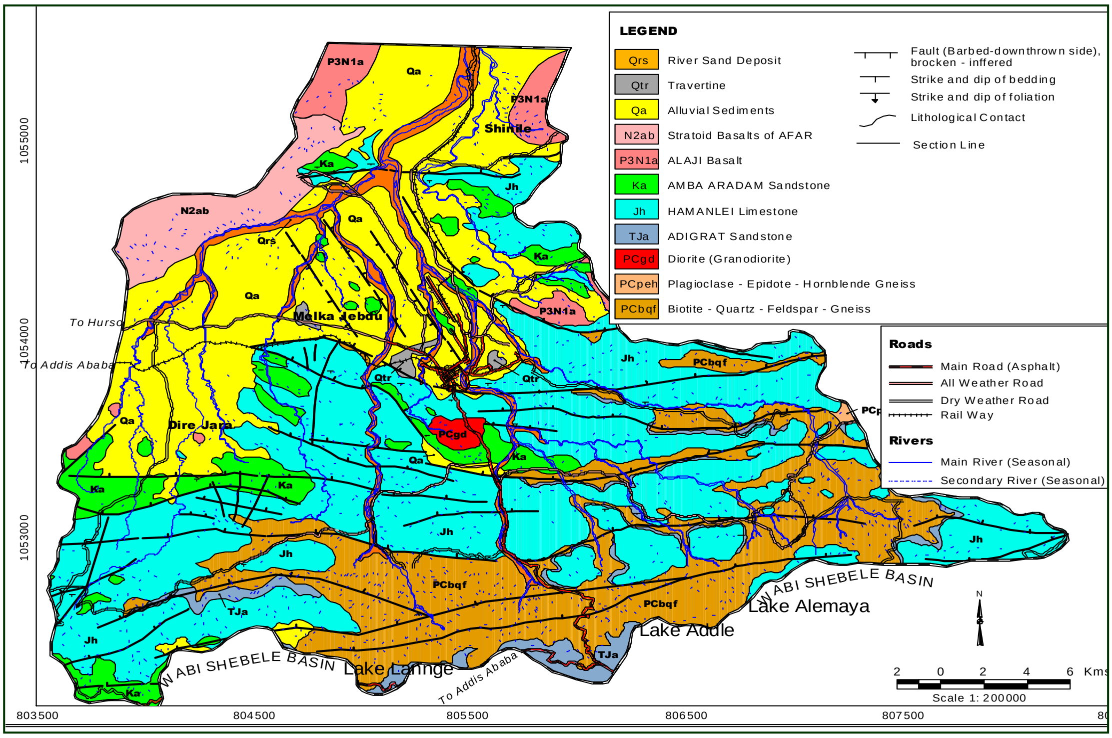

Fig.7 Geology of Map Dire Dawa area (Mirus ,2003 & WWDSE, E.Abate ,2004)

The generalized geological events of the Dire Dawa and surrounding areas are shown in the following table.2 and annexed-IV

Table .2 The geological events of Dire Dawa area (WWDSE, 2004)

Chronology		**Events**	**Lithological formation**
Cenozoic	Quaternary	Fluvial activities and Young volcanic eruptions	Alluvial deposits and basic Volcanic rocks
	Pliocene	Volcanic eruptions and Rift formation	Pyroclastic and lava deposits
	Tertiary	Uplifting and erosion	Trap volcanoes
	Miocene		
	Eocene		
	Paleocene		
Mesozoic	Cretaceous	Regression	Upper sandstone
	Jurassic	Transgression	Antalo limestone
			Adigrat sandstone
	Triassic	??	
Paleozoic		**Peneplanation**	??
Precambrian		Intrusion and metamorphism	High grade metamorphic rocks

According to Habteab & Jiri (1986) and Mesfin A.(1981), the area consists of three tectonic units: the plateau, the escarpment and the depression. The plateau and escarpment is dominated by E-W or ENE-WSW trending faults and perpendicular to the drainage system in the area. The blocks are downthrown to the north and form the boundary of the rift system. Abrupt change in slope gradient on the escarpment causes decreases in velocity of surface water, which has resulted in forming fans at the foot of the escarpment.

3.2 Hydrogeology and Aquifer properties

Many valuable geological and hydrogeological works have been done by Tesfamichael (1974) and Ketema (1982) in the Dire Dawa area and surroundings. Associated Engineering Survey Ltd. Canada (1982) had also done a feasibility study for Dire Dawa water supply. Integrated Resource Master Plan of ADDC study has been undertaken by the WWDSE (2004) and Dire Dawa Water Mines and Energy Office and others had conducted a lot of studies in this research area.

From drilling results (MoWR, 1999a), it was found that the upper sandstone was overlain by alluvium at the Sabiyian wells. The upper sandstone was penetrated after drilling through alluvium and basalts at Dire Jara well field and TW4 (north west of Dire Dawa town). The upper sandstone is intruded by basaltic dykes, sills and batholiths and extensively faulted which makes the unit a potential aquifer in the basin. The drilled wells in the aquifer show that the thickness of the aquifer is variable. The thickness of the aquifer penetrated at the Dire Jara well field is 36 meters (W-4) and at TW4 is 108 meters. Furthermore, most of the production wells at Sabiyian and Dire Jara well field do not fully penetrate the sandstone aquifers.

From TW-4 information, the groundwater was struck at 98 meters depth and the static water level stabilized at 31 meters. It is recorded in the Dire Jara well accomplishment report (WWDSE,2001) as a general conclusion that the groundwater was struck from 100-120 meters and the static water level is stabilized at 50 to 60meters below the ground surface. The sandstone at the Sabiyian area is also considered as a confined aquifer although the pumping test results show leaky aquifer (MoWR, 1999b). In general the main aquifer is confined aquifer in the region where the confining layer could be basalt, clay and intercalation of shale with in the sandstone.

Drilling results (WWDSE, 2001) show that the limestone unconformablly underlies the upper sandstone (see Annex-IV). The limestone at Dire Jara area is highly fractured and karsted , forms a complex water bearing formation together with the upper sandstone; where as at Dire Dawa town, the limestone is massive with low groundwater productivity.

3.2.1 Types of Aquifer and Hydraulic Properties

In the previous studies of the hydrogeological condition of the surrounding areas according to EIGS (1986), WWDSE (2001) and Mesfin (1981) the main water bearing formation has been classified as follows:

1. Extensive alluvial sediments aquifer with intergranular permeability
2. Localized volcanic rocks aquifer with fracture permeability
3. Extensive sedimentary formation aquifer (sandstone & limestone) with fracture permeability

Different studies have been conducted in the area on the hydrodynamic characteristics of the geological formations gives the values of specific capacity, yield and transmissivity determined form boreholes (pumping test) and measured spring yields to categorize the aquifers of the area. The categorized aquifers are given in table annexed-III (aquifers type and their productivity). Minalha (2007) classified the ground water into two layer aquifer systems such as the upper unconfined aquifer (layer 1), and the lower more productive confined aquifer (layer 2).

The main hydstratigraphic aquifer units in the study area identified by WWDSE (2004) are:

Alluvial aquifers: alluvial sediments are distributed in Dire Dawa groundwater basin, unconfined unit composed of clay, silt, sand, gravel and rock fragments. The groundwater depth on average varies in the alluvial sediments from 15 to 50 m with the mean values of saturated media is about 20 m. The bottom elevation of this layer is estimated to be 900m a.s.l. The transmissivity of the alluvial formation as obtained from pumping test results varies from 8 to 700 m^2/day. Transmissivity is directly proportional to horizontal permeability (K) and thickness (b) of the saturated aquifer.The estimated average value of transmissivity (T) and hydraulic conductivity (K) is 27.5m^2/day and 1.4m/day ($\approx 1.5 \times 10^{-5}$ to 10^{-3}m/s) respectively (WWDSE, 2004). The summarized values of transmissivity by Minalha (2007) are given in the table.3. The mean value of K is very important for prediction and assimilation of transport model in the phreatic aquifer.

Table.3 Summary of transmissivity of the different geological formation (Minalha, 2007)

Geological Formation	Transimissivity in m^2/day					Aquifer productivity
	Min	*Max*	*Mean*	*Harmonic mean*	*Median*	
Alluvial (Qa)	**7.8**	**712.8**	**103.8**	**27.5**	**44.3**	**Moderate**
Basalts (P)	**2.4**	**9.9**	**6.0**	**4.3**	**5.7**	**Very low**
Upper SS and Hamanlei LS (Ka+Jh)	**9.0**	**5512**	**1801.9**	**88**	**375.3**	**High**

Tertiary volcanic rocks: These rocks refer to the stratiod and Alaji basalt outcrops that occupy the elevated areas at the north and northeastern part of the area. This formation is generally a regional aquiclude and is the confining layer for the lower highly productive confined aquifer with transmissivity less than $5m^2$/day (the average T value is $5.7m^2$/day). For modeling purpose this unit is assumed to have a constant thickness of 50m.

Cretaceous upper sandstones: this unit is found below the confining layer and alluvial deposits in most part of the lower part of the study area. The drilled wells in the aquifer show that the thickness of the aquifer is variable. The minimum thickness of the aquifer penetrated at the Dire Jara well field is 36m. However the estimated average thickness of the unit is 200m (Tesfamichael, 1974). The static water level varies from 10m (Sabiyian) to 70m (Dire-Jara) with the specific discharge of 0.13 to 68 lit/sec/m.

Jurassic Hamanalei limestone: the drilling results show that the limestone uncomfortably underlies the upper sandstone. The limestone in the study area could not be independently characterized and the aquifer characterization for the upper sandstone applies also for the limestone. The lower part of the limestone is a gray-white limestone inter-bedded with shale overlain with oolitic limestone and the upper part is well-bedded gray fossiliferous limestone (Seife B. 1982, Habteab Z. & Jiri S.1986).

In the Sabiyan Wellfield, there are nine production wells which were constructed by 1987 in the western expansion part of the city. The wells have the capacity to supply about 250 l/s for the entire city population. The Sabiyan well field has two types of aquifers (MoWR, 1999a); one is a shallow unconfined aquifer in the recent deposits about 15 to 25m depth while the second aquifer is situated in the deeper quartz sandstone with water bearing fractures at depths greater than 35m. Six of the boreholes were completed in the main quartz sandstone aquifer and one borehole (PW-8) was completed in calcareous sandstone.

3.3. Groundwater Resources and Anthropogenic Activities

Urbanisation as a driving force; the increasing size and population of cities and towns is facilitated by the ‘pushing-pulling factors’, migration from rural areas due to a major environmental change. During the twentieth century, the world’s rural population will be doubled but the urban population increased more than tenfold (WWAP, 2006). A lot of changes will be faced as a result of urbanization.

Wastes generated from the urban environment may be contaminated the aquifer as well as affected the quality of water in the area (Wondewosun, 2003). The poor sanitation condition together with the lack of proper waste disposal mechanisms attributed to sever effect of pollution of both surface and ground water resources of the area. As Lerner, (2003) presented the most sever effect of pollution was observed in shallow wells, which is the reflection of all anthropogenic impact on water bodies of the area. Assessing the fate and behaviour of the NPS (Non Point Source) pollutants is a complex environmental problem due to heterogeneity of the subsurface system and the spread of NPS over large areas in relatively low concentrations (Al-Zabet 2002). Depending on the local conditions, the same anthropogenic influence does not always cause the same effects of the same magnitude. By analysis of the correlation coefficients and a factor analysis, groups of parameters which originate from common sources were derived but also influenced by anthropogenic factors (Schiedek et al.2008).

3.3.1 Land use System and Urbanization

Dire Dawa is one of the fast growing towns in Ethiopia. It has recorded a dramatic growth since its foundation. The first Master plan of Dire Dawa was prepared in 1967 that has now become outdated. The land use master plan that dates back to late 1967 and 1994 (NUPI-National Urban plan Institute) indicates that the total planned area was 2928 and 3241 hectares respectively. By the year (2004), the town extended to 8386 hectares (Fig.8) and still the town is expanding.

The land use system of the town is dominantly mixed as shown in Fig.8, especially residential areas with commercial activities. This is true notably in the central part of the town where almost all buildings along the streets are used for commercial activities and their backyards or internal courtyards are used for dwelling purpose. Residential areas cover around 680 ha (10%); squatter settlement is estimated 980 ha (12%) and all about consists of 50% of the total built-up area.

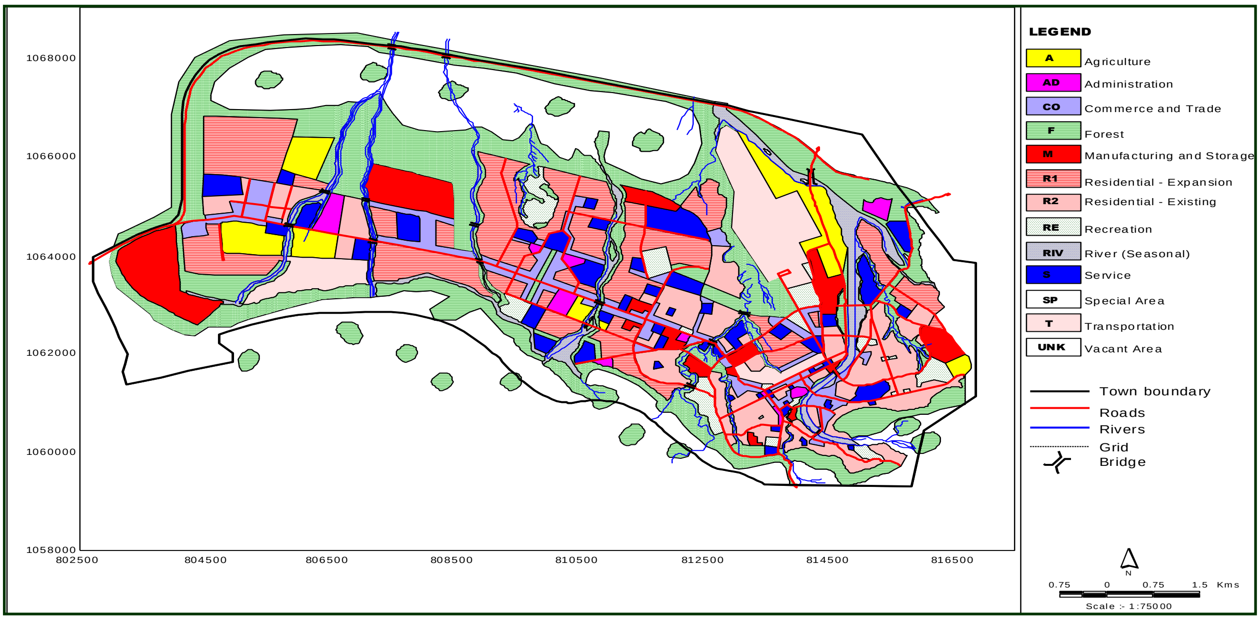

Fig.8 Land use and urbanization map of Dire Dawa (modified from NUPI 1994, WWDSE 2004)

The major activities undergoing in the town which contribute for the groundwater pollution:

1. Industrial activities: Industry is the second important economic activity in urban area. There are six major industries and more than 100 small scale manufacturing industries in the town of Dire Dawa. These are Dire Dawa textile, Dire Dawa food complex, ELFORA meat processing, East Africa bottling (soft drink), and Dire Dawa Cement.

Dire Dawa Cement Factory: Major wastes and byproduct of the factory are carbon dioxide, carbon monoxide, dust and sometimes sulfur dioxide. Carbon monoxide is produced when there is incomplete combustion of raw material. The main raw material is lime ($CaCO_3$). This lime when it partially combusted gives cement, CO_2 and CO. Both CO_2 and CO release to the air, which ultimately contribute to the green house effect in the atmosphere. Sulfur dioxide that liberates from the factory has been causing bad smell for the nearby residents.

Dire Dawa Textile Factory: The Dire Dawa textile factory is the main source of contaminant in the urban area. The chemicals used in this factory pollute the ground and surface water. The factory has no waste treatment plant and it directly releases all sort of wastes into the stream channel. Most of the time, pH of the waste is more than 12. The chemicals used for cotton preparation and dying are hydrogen peroxide (H_2O_2), sodium hydroxide (NaOH), sodium sulfite and sodium chloride.

In the town, there are about 100 medium and small-scale factories. All medium and large-scale industries do not treat their effluent or liquid waste. They simply discharge in the open field, near by the dry river channel or sandy stream channel. Mostly the residents are settled in the center as shown in the population density map (Persons/ha) of Dire Dawa (Fig.9). The centre of the town is highly populated around 350-500 per hectare which directly or indirectly contribute to the groundwater pollution.

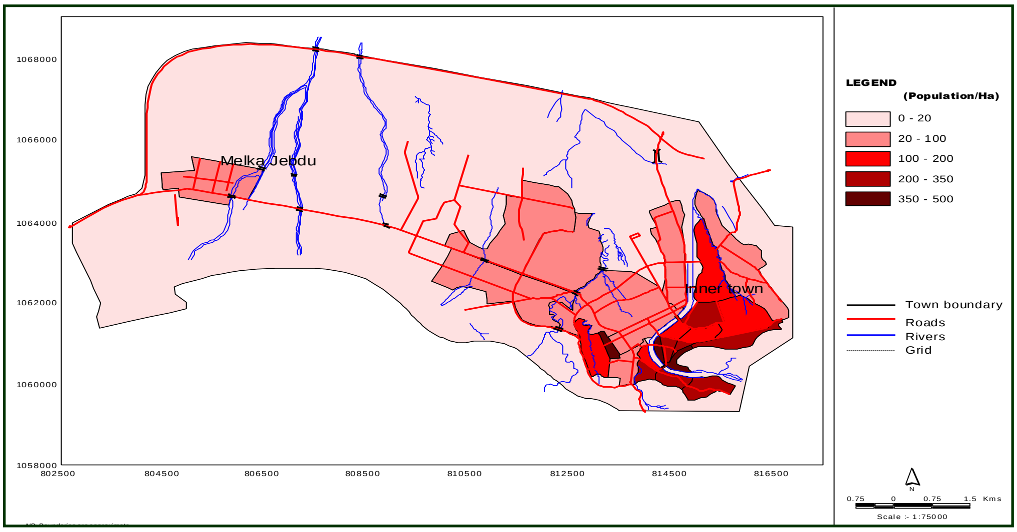

Fig.9 Population density (Persons/ha) map of Dire Dawa (Abate, MoWR, 2004)

ELFORA-Dire Dawa meat processing plant: Solid waste has been dumped at the public waste disposal site while the liquid waste has been discharged into the stream channel. When the plant functions with its full capacity, the load would be significant to cause environmental pollution and contamination of surface and ground water around it.

2. Municipal Wastes: Domestic wastes have been discharged directly into the open ditches and sandy streams. Degradation of ground water quality is intensifying by point sources such as septic tanks, pit latrines and industrial effluents. There are also other pollution sources in Dire Dawa like markets, cemeteries, fuel stations, garages and etc. The waste generated from the market centers are various types and are not systematically collected. As a result, it may contribute for the worsening of groundwater in the study area.

In Dire Dawa town, there is no central municipal sewerage system at present. Each household is in charge of disposing of its’ own waste at any open place in their surroundings. One of the problems facing urban settlements is the skill to cope with increasing quantity of wastes both solid and liquid wastes, in spite of the growing demand of the population.

As a result urban settlements are facing with serious health and environmental complications, as the existing sanitation conditions turn out to be worst by unrestrained population increase and urbanization. For example the distributions of housing units or households are made by types of toilet facilities used shown in the table.4 below. As to the information obtained from CSA (1998) the sanitation facility coverage is more than 75% in the town of DDAC.

Table.4 Urban toilet facilities of Dire Dawa by housing unit (CSA, 1998)

Towns	All Housing units	**Type of Toilet facilities**					
		Has no Toilet	Flushed Toilet private	Flushed Toilet shared	Pit Private	Pit Shared	Not stated
Dire Dawa	34680	20%	4.6%	2.3%	28.3%	37.7%	1.8%
MelkaJebdu	1702	2.8%	-	-	1.5%	0.25%	-
Dire Dawa	36382	23.4%	4.6%	2.3%	29.8%	38%	1.8%

The solid waste disposal system is generally weak. The solid waste collection mechanisms and location sites of containers are not systematically in place. The dumping site also has conducted at open fields. Solid waste/garbage disposal situation in Dire Dawa town, as per 1998 CSA data is indicated in the table.5 below.

Table.5 Solid waste/garbage disposal situations in Dire Dawa (CSA, 1998)

Status	**Vehicle container**	**Dug out**	**Thrown away**	**Others**	**Total**
Rural	3.1%	1.1%	93%	2.8%	100%
Urban	46.55	11%	37.4%	5.1%	100%

As to the conservation strategy document prepared in the year 2000, the solid waste collection and disposal situation in Dire Dawa is 76% dump outside in an open field, 14% in pit, and 10% burning.

3. Agricultural Wastes: In the city and its vicinity, there are numerous urban agricultural activities such as Tony farm, ‘chat’ farm, Amdael diary farm, Hafecat diary, and other small-scale cattle breeding and horticulture producers in the town. Generally, the agricultural inputs and by-products are the major constitutes of wastes and have a chance to contribute for the groundwater pollution. Animal wastes are classified as solid and liquid. Such animal waste may become the source of groundwater pollution.

3.3.2 Groundwater Quality Degradation

Results from laboratory analysis which was conducted on water samples taken from different localities at different times indicate that the level of groundwater pollution is increasing at an alarming rate. For instance, according to the hydrochemical analysis conducted by an Israeli geologist (Greitzer, 1959), the maximum concentration of NO_3^- at the centre of the town was 45mg/l. After twenty-two years by Ketema (1982) reported 230mg/l NO_3^- concentration observed within Dire Dawa town. On the other hand, water sampled by MoWR (2003) from Dire Dawa food complex borehole (FBH) was analyzed by EIGS-laboratory and an even higher concentration (266mg/l) of nitrate was observed.

According to Taye (1988) Dire Dawa town is a fast growing industrial and commercial town, which produces pollutants in large amount. The degree of nitrate concentration in the groundwater also depends on the population density; recharge condition and geological nature of the area.The domestic as well as industrial wastes have been discharged directly into the open ditches and sandy alluvial flashing streams. From the nature of its topography and soil, the groundwater resource of the study area is very sensitive to pollution.

3.3.3 Nitrate and its sources

Nitrate is a chemical compound of one part nitrogen and three parts oxygen that is designated by the symbol “NO_3^-”. It is the most common form of nitrogen found in water. In water, nitrate has no taste or scent and can only be detected through a chemical test. The Maximum Acceptable Concentration (MAC) for nitrate in drinking water in British Columbia (BC) is 45mg/l while according to WHO's drinking-water quality, set up in Genea 1993 is 50 mg/l of total nitrogen. For laboratory tests reported as nitrate-nitrogen (NO_3^- N, the amount of nitrogen present in nitrate) the MAC is 10 mg/l (BC, 2007).

1. Sources of nitrate: There are many sources of nitrogen (both natural and anthropogenic) that could potentially lead to the pollution of the groundwater with nitrates; the anthropogenic sources are really the ones that most often causes of nitrate to rise to a dangerous level. Waste materials are one of the anthropogenic sources of nitrate contamination of groundwater. Many local sources of potential nitrate contamination of groundwater exist such as, "sites used for disposal of human and animal sewage; industrial wastes related to food processing, munitions, and some polyresin facilities; and sites where handling and accidental spills of nitrogenous materials may accumulate" (Hallberg and Keeney, 1993). Septic tanks are another example of anthropogenic source nitrogen contamination of the groundwater. Groundwater contamination is usually related to the density of septic systems (Hallberg and Keeney, 1993). In densely populated areas, septic systems can represent a major local source of nitrate to the groundwater. However in less populated areas septic systems don't really pose much of a threat to groundwater contamination.

2. Nitrate in groundwater system: According Wakida (2008) the rapid growth of urban population in developing countries leads to unplanned settlements where limited pit latrines or septic tanks are the only options available for sewage disposal. Urban sources of nitrate-N may have a high impact on groundwater quality because of the high concentration of potential sources in a smaller area than agricultural land (Wakida and Lerner, 2005). The mobility of N with respect to groundwater is related to chemical properties that affect the ease of transport with water and adsorption to soil particles. Nitrate (NO_3) is the most mobile form of N because of its high solubility and negative charge (Seelig & Nowatzki, 2001).

Ammonia is produced by the breakdown of organic sources of nitrogen; being a major constituent of proteins and nucleic acids. Municipal wastewaters contain large amounts of organic wastes, so the wastewater will have a high ammonia concentration. With this high concentration of ammonia, the wastewater would harm downstream ecosystems if released (Henze et al.1997). Ammonia is toxic to aquatic life at these concentrations, and the nitrification process requires oxygen (ammonia contributes to the BOD of the wastewater) so it will use up the oxygen needed by other organisms.

The rates of nitrification reaction are highly dependent on a number of environmental factors. These include the substrate and oxygen concentration, temperature, pH, and the presence of toxic or inhibiting substances (Butcher et al, 1992). According to Butcher et al (1992) one striking aspect of environmental nitrogen chemistry is the coexistence of reduced compounds (ammonia N oxidation state = -3) and fully oxidized species (e.g., nitrate N oxidation state $= {}^{+}5$). This results from chemical and biochemical processing that occurs in both aerobic and anaerobic environments.

Bacteria play an important role as catalysts in almost all nitrogen transformations in nature. In microbiology (Krumbein, 1983; Zehnder, 1988) the two important overall reactions are denitrification and nitrification. Denitrification stimulates the reduction of nitrate to $N_2(g)$ by bacteria, through a complicated pathway involving intermediates like nitrite. It should be noted that denitrification is not a reversible reaction. During nitrification, bacteria oxidize amines from organic matter to nitrite and nitrate.

3. The environmental health concerns: Though nitrate is considered relatively non-toxic, a high nitrate concentration in drinking water is an environmental health concern because it can harm infants by reducing the ability of blood to transport oxygen. In babies, especially those under six months old, *methaemoglobinaemia*, commonly called “blue-baby syndrome,” can result from oxygen deprivation caused by drinking water high in nitrate. Methemoglobinemia is the condition in the blood which causes infant cyanosis, or blue-baby syndrome. Methemoglobin is probably formed in the intestinal tract of an infant when bacteria convert the nitrate ion to nitrite ion (Comly, 1987). One nitrite molecule then reacts with two molecules of hemoglobin to form methemoglobin. In acid mediums, such as the stomach, the reaction occurs quite rapidly (Comly, 1987). This altered form of blood protein prevents the blood cells from absorbing oxygen which leads to slow suffocation of the infant which may lead to death (Gustafson, 1993; Finley, 1990).

4. Water Quality Analysis and Hydrogeochemical processes

4.1 Water types and its sources

Water analyses (Annex-I and Table.6) show that the groundwater composition is highly mixed and modified by manmade and natural factors. The major sources of anions like sulphate, and chloride are of sedimentary origin like gypsum and halite. Bicarbonate may be from both sources; dissolution of carbonate rocks and silicate weathering processes. It needs to be conceptualized in order to trace the source rock and the contribution of different minerals in the groundwater system.

The water quality result has changed due to different sources (rain and spring water and water from Bh $_{\text{(inner-town)}}$ & Bh $_{\text{(out-down)}}$) and involving mechanisms. The chemical composition of waters varied from place to place through groundwater evolution on major cations and anions. In the Table.6 the sampling sites are located from upper part of the basin (FSP-5 Fechass Spring) towards the lower part of Shinile Bh (downstream). The values of nitrate and chloride have similar trend. At TDW-1 (Tsehaye dug well) values increased which is 155mg/l nitrate and 197mg/l of chloride due to some sort of modification at this area. The nitrate value goes down (i.e 44mg/l) at the downstream of Shinile Bh (SnBh-1) by denitrification process and other mechanisms. Nitrate is the most mobile form of N because of its high solubility and transport with water and adsorption by soil particles. Ammonium (NH_4^+) is missed in laboratory sample analysis but the are many possible sources from municipal wastes. The pH of rain water also is not indicated.

Table.6 Water sample laboratory result (mg/l) from Dire Dawa (EGS, 2003)

Field code	pH	Na	K	Ca	Mg	HCO_3	Cl	SO_4	F	NO3	Sio_2 (aq)	Elev(m)
DD-Rain	*	1.26	2.6	14	1	*	3.33	13	-	15	-	-
FSP-5	7.0	64	0.9	128	23	415	91	40	0,62	66	48	1380
TDW-1	6.78	95	4,9	168	55	508	197	97	0.61	155	43	1160
SnBh-1	7.3	68	1.9	118	48	462	101	99	0.66	44	49	960

NB.DD-Rain Dire Dawa rain water sample, FSP-5 Fechass spring (up streams), TDW-1,Tsehaye Hotel hand dug well (inner part of the town) and SnBh-1 Shinile Bh (down streams)
The values of *pH and HCO_3^- of rainwater are missed from laboratory result

The accuracy of chemical analysis -The recalculation of the water chemical analysis in the table.7 is mainly on the four major cations (Na^+ , K^+, Ca^{2+}, Mg^{2+}) and the four major anions (HCO_3^-, Cl^- ,SO^{2-}_4, NO^-_3). The graphical presentation of those water compositions from the three different sites are shown in Fig.10 on Piper diagram.

Table.7 Recalculation of water sample into mmol/l from (mg/l/ (gram formula weight)

Field code	DDR-Rain	FSP-5	TDW-1	SnBh-1
pH	*	7.0	6,78	7,3
Na^+	0.055	2.78	4.13	2.96
K^+	0.066	0.23	0.125	0.049
Ca^{2+}	0.350	3.20	4.2	2.95
Mg^{2+}	0.041	0.95	2.26	1.97
Σ (meq/l)=	**0.903**	**11.31**	**17.175**	**12.849**
HCO_3^-	*	6.80	8.32	7.57
Cl^-	0.093	2.57	5.56	2.85
SO_4^{2-}	0.135	0.416	1.01	1.03
CO_2 (TIC) ?	-	1.07	2.77	0.91
F^-	-	0.032	0.032	0.035
NO_3^-	0.24	1.06	2.5	0.71
$Sio_2(aq)$	-	0.8	0.72	0.82
Σ (meq/l)=	**-0.903**	**-11.294**	**-17.422**	**-13.225**
ΔΣ(meq/l) =	**+0.0**	**+0.016**	**-0.247**	**-0.376**
(E.B%)=(Σ⁺ - Σ⁻)/ (Σ⁺ + Σ⁻)	**16 %**	**0.07%**	**0.71%**	**1.45%**

*HCO_3^- of the rain water sample result is missed; then value calculated based on the mass balance approach from sum of cations and anions in its meq/l (0.903) relations is about 0.299mmol/l by ignoring the contribution of anions the of (TIC) CO_2 & SiO_2^{2-} . Most rainwater has a pH of 5.6 to 5.8, simply due to the presence of carbonic acid (H_2CO_3) but we can assume that *pH of rain water is greater than 6.3 at abnormal bacisity condition for the formation of bicarbonates.

$$\textbf{Electrical Balance (E.B\%)} = 100 * \frac{\textbf{(Sum of Cations + Sum of anions)}}{\textbf{(Sum of Cations - Sum of anions)}}$$

The accuracy of chemical analysis can be checked by applying the Electrical Balance (E.B %) formula. Based on the formula, the rain water sample, it shows some error problem since it is not a completed result. The sum of cations and anions of rain water is imbalance because the result of Electrical Balance (E.B %) is about 16%. It is unacceptable value and it might be a technical error during laboratory analysis. The composition of rain water sample is also modified by natural and manmade factors. On the other hand the chemical analysis of spring water and water from TDW-1 and SnBh-1 results fall within the acceptable range (less than 5%).

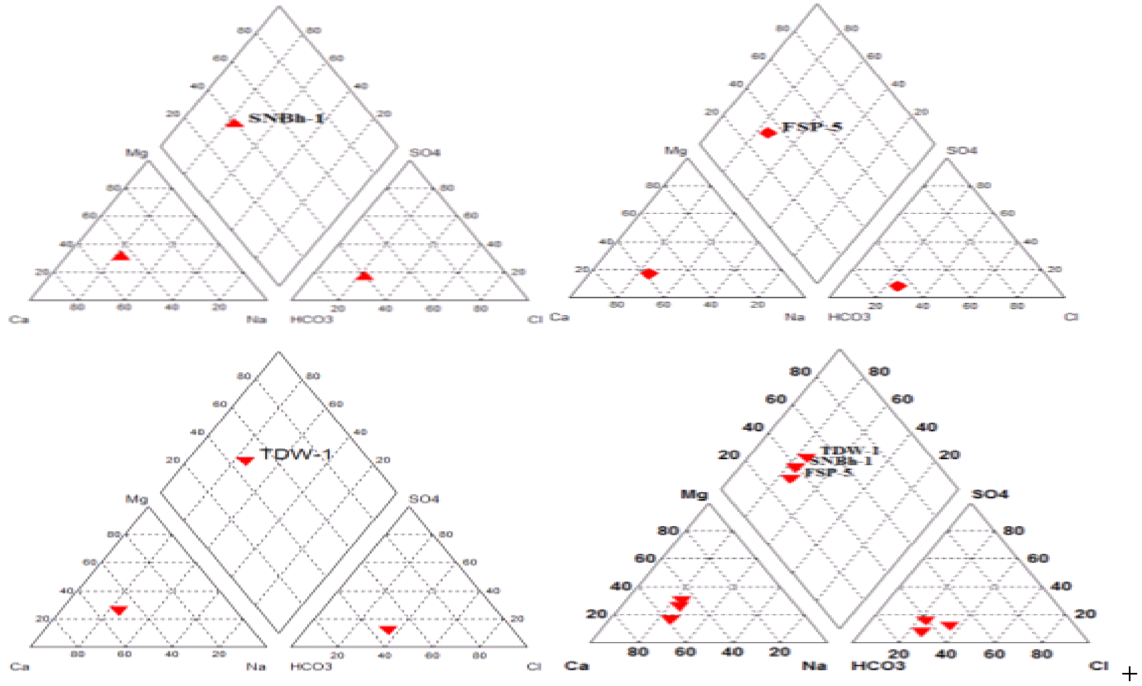

Fig.10 Piper plots of water types from Dire Dawa Area

NO_3^- is not plotted on the Piper diagram, only major ions in AquaChem software.

The fact that the Red Sea is close to the study area and the presence of several industries (for instance cement factory) in the nearby towns could generate possible sources of Na^+, $Ca^{2+}$and Cl^- ,SO_4^{2-}, NO_3^-. The major water types from the spring is Ca-Na-$HCO_{3(upstream)}$ possibly due to dissolution and weathering processes. As a result of human intervention the water quality result from the inner part of the town is dominated by Ca-Na-Mg-HCO_3 -Cl /$NO_{3(inner\ part)}$.The chlorides, sulphates and sodium modification of the water from inner Bh is crucial influenced by human interference. The water quality also changed down wards out of the urbanized part of the town. The change of water types are mainly depending on the geochemical evolution and water-rock interaction as shown above on the Piper plot diagram (Fig.10). The resident period and source of recharge are other factors which control water type with the activity of pH and the dissolution processes.

From the Piper and Stiff plot diagrams the water samples can be divided into three types from its source and locality of sampling points (Fig.10 and Fig.11):

A. The spring water (FSP-5) from the upstream is mainly Ca-Mg-Na-HCO_3 type dominated
B. Borehole water (TDW-1) from the inner part is Ca-Na-HCO_3-Cl/NO_3 type dominated.
C. Borehole water (SnBh-1) from down stream is Ca –Na -HCO_3 -Cl type dominated.

*NO_3^- is not plotted on the Piper and Stiff- diagram, only major ions in AquaChem software

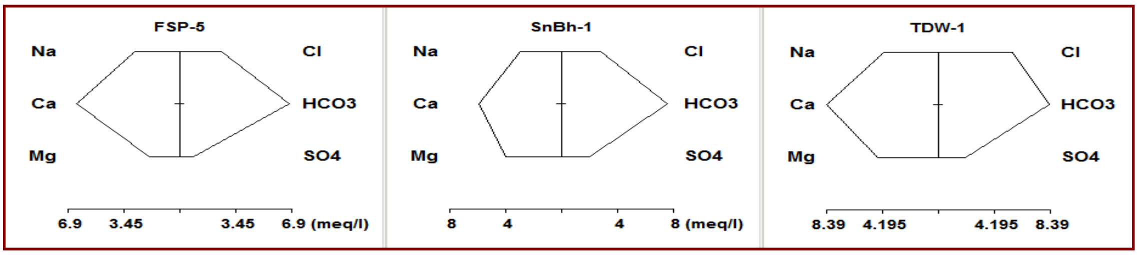

Fig.11 Stiff plot diagram of the three water types (FSP-5, SnBh-1 & TDW-1)

The major water types from the springs are Ca-Mg-HCO_3 through weathering process while the water from the Bh in the inner part of the town is dominated by Ca-Na-Mg-HCO_3 . The chlorides and sodium modification of the water is mainly the human interference in the Dire Dawa town since the shallow wells are near the residential squatter. The resident time and source of recharge area are also another controlling factor for groundwater evolution and water types. Geologically, the sedimentary and metamorphic basins have observed in the project areas which contribute to Ca-HCO_3 water type dominated by the dissolution and silicate weathering processes.

4.2 Hydrogeochemical processes

The schematic presentation here in Fig.12 shows that the input-output relation of rain water-spring water and spring water-Bh_{inner} water and also from Bh_{inner}-$Bh_{out\text{-}down}$ with the dominated water types along with the geological x-section of the study area (annex-IV). Naturally, the upstream is the recharge area and the water is similar as the water in the source rock of the area where as in the downstream more of modification by natural hydrogeochemical evolution and manmade factors.

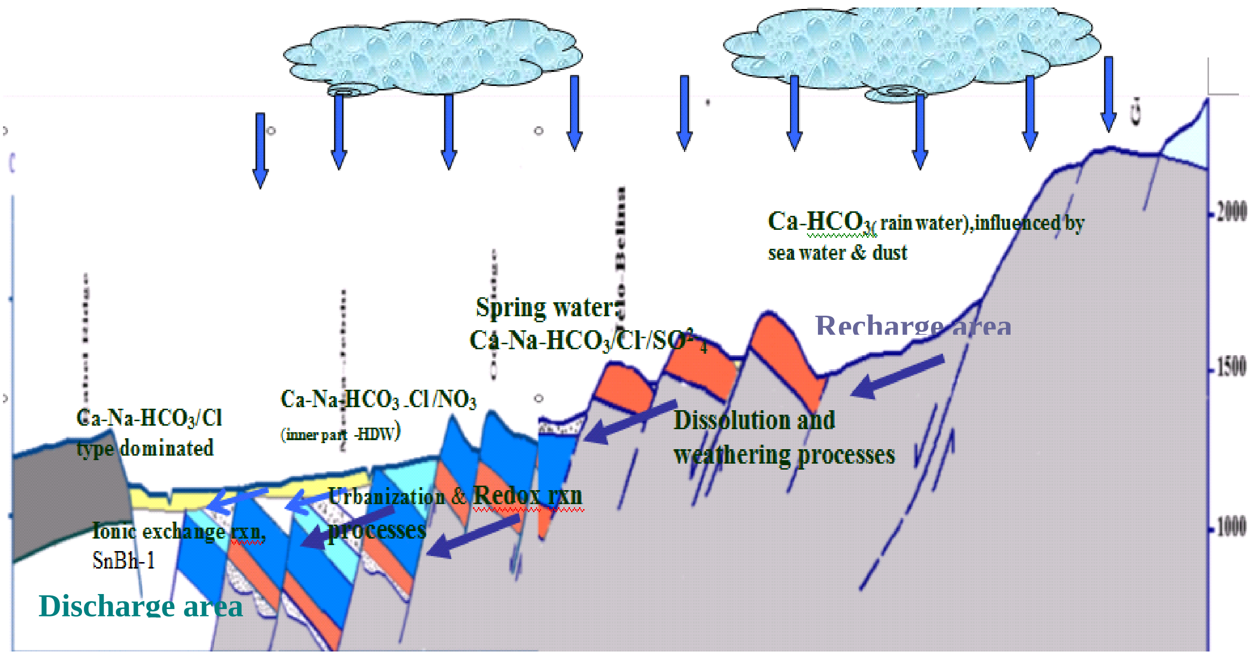

Fig.12 The schematic model of water- rock interaction in relation of discharge-recharge areas

4.2.1 Silicate weathering and carbonates

The water type of the spring is mainly bicarbonate (Ca-Mg/Na-HCO_3). Most of the springs originate from the escarpment part of the region. The limestone unit and fractured basement complex of the region making a favorable condition for the origin of springs which contribute for the bicarbonate water. The mass balance approach is important in weathering process to trace the relative changes of water chemistry though the dissolution or precipitation of minerals and in order to estimate the parent materials that the minerals contributed on it. The possible hydrogeochemical processes and the major activities at (A, B, & C) is presented by the simple the schematic conceptualize model (Fig.13). **Reactant phases $\longrightarrow$ weathering residue + dissolved ions**

Calcium (Ca^{2+}) is one of the principal cation from both sedimentary carbonate and metamorphic plagioclase faces. Its source is mainly the dissolution of calcite, aragonite, dolomite and Ca-feldspar through geochemical processes. $CaCO_3$ is soluble in abundant hydrogen ion derived from the dissociation of carbonic acid under favorable pH. On the other hand the possible source of Na^+ is acidic rock from granite metamorphic- sodic plagioclase groups and also possibly halite from some lake connection since chloride is very high in the spring sample upstream. The common source for Cl^- is halite (NaCl); spring might be connected with lake water in the upstream area. In this analysis assume that we ignored the contribution of Cl in silicate weathering calculation.

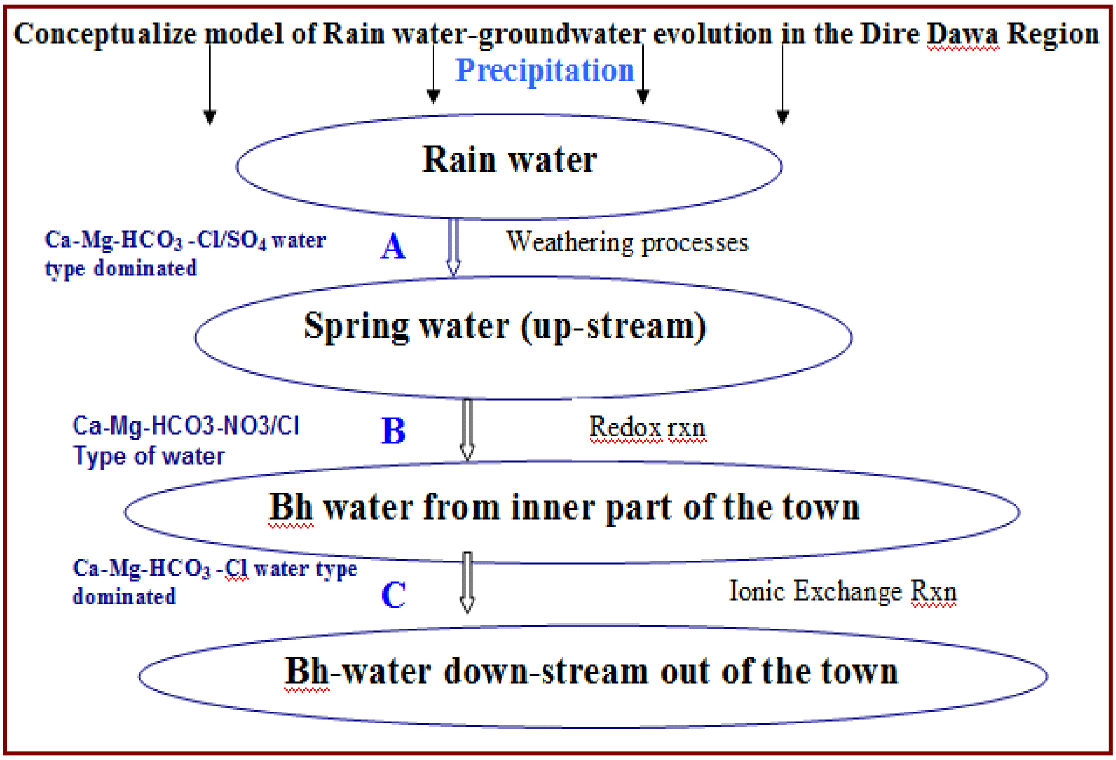

Fig.13 The graphic presentation of rain water-groundwater evolution in Dire Dawa area

There are a lot of sources for bicarbonate (HCO^-_3) water depending on the pH activity. In the table.8 below the water composition of spring is possible the product of dissolution of carbonates and silicate weathering reactions. The concentration in rain water subtracted from the spring water to obtain the contribution of rock weathering through water- source rock interaction.

Table.8 The contribution of weathering from silicates/carbonates of (FSP-1) spring water (mmol/l)

Code	pH	Na	K	Ca	Mg	HCO_3-	Cl	SO_4^{2-}	F	NO_3-	Sio_2 (aq)
DD-Rain	?	0.055	0.066	0.35	0.041	* 0.299	0.093	0.135	-	0.24	-
FSP-5	7	2.78	0.23	3.2	0.95	6.80	2.57	0.416	0.032	1.06	0.8
weathering		2.725	0.164	2.85	0.909	6.501	2.477	0.281		0.82	0.8

From the spring water chemistry it is possible to estimate the mineral sources/parent rock material. Halite (NaCl), gypsum ($CaSO_4$), plagioclase, calcite ($CaCO_3$) and silica (quarz SiO_2) are the most primary minerals present in the rocks that contribute for the spring water composition in upstream areas. The differences in composition between the rain water and perennial springs are due to reactions between water and rocks/minerals it contacts probably a longer residence time in the subsoil.

Carbonates/CO_2 and major cations: The occurrence of carbonates and bicarbonates in spring water is largely dependent on pH value. From the theoretical background, at pH greater than 10.3 the dissociation of bicarbonate ions into carbonate ions is the predominant species. At PH less than 10.3 most carbonate ions become bicarbonate ions. HCO_3 is more abundant at pH< 10.3. The production of bicarbonate is very high at low pH and open system.

The most common carbonate minerals in spring water are calcite ($CaCO_3$) and dolomite ($CaMg(CO_3)_2$). The carbonate reactions are very important to control the groundwater chemistry. Springs have excessively higher hardnesses. The hardness of spring water also depends mainly on the presence of dissolved calcium and magnesium from carbonate rocks with bicarbonate anion associated with limestone and dolomite. The major causes of hardness is water passes through or over deposits such as limestone, the levels of Ca^{2+}, $Mg^{2+,}$ and HCO_{3-} ions present in the water can greatly increase and cause the water to be classified as hard water. Total hardness of FSP-5 spring water in Dire Dawa is around 8.3meq/l by applying the formula **(TH= 3.2Ca*2 + 0.95Mg*2 =8.3meq/l).** Total hardness is a measure of the amount of calcium and magnesium, and is expressed as calcium carbonate.

4.2.2 Water quality modification and Ionic exchange process

Reduction and oxidation processes play a great role for the change of water quality in the groundwater evolution with the contribution of natural phenomena and manmade inputs. In table.9 the value of major cations and anions have increased from FSP-5 spring towards the Tsehaye dug well (TDW-1) in the inner city as a result of certain inputs. The concentration of nitrate becomes excess in the shallow wells of the city. Bacteria in water quickly convert nitrites (NO^-_2) to nitrates (NO^-_3) mainly by nitrification. The geochemical processes are enhanced for the change of water quality from (TDW-1) to the downstream of Shinle bore hole (SnBh-1) in the basin that presented at (Fig.12 and Fig.13) above.

Table.9 Spring-borehole water geochemical evolution (mmol/l) in Dire Dawa

F.Code	pH	Na^+	K^+	Ca_2^+	Mg_2^+	HCO_3^-	Cl^-	SO_4^{2-}	$CO_2^{\ 2-}$	F^-	NO_3^-	Sio_2 aq)
FSP-5	7	2.78	0.23	3.2	0.95	6.8	**2.57**	0.416	1.07	0.032	**1.06**	0.8
TDW-1	6,78	4.13	0.125	4.2	2.26	8.32	**5.56**	1.01	2.77	0.032	**2.5**	0.72
SnBh-1	7,3	2.96	0.049	2.95	1.97	7.57	**2.85**	1.03	0.91	0.035	**0.71**	0.82

In the table.9, the concentration of major cations and anions are changed in groundwater at TDW-1 station where as moving downstream (SnBh-1) at the sometime it become decreased the dilution processes. Hydrochemical results show that there is some sort of artificial inputs discharged into the aquifer that easily join and modified the groundwater quality. From Fig.14we can understand that there is clear sorption or dissolution process going on between TDW-1 (inner) and SnBh-1 in the downstream.

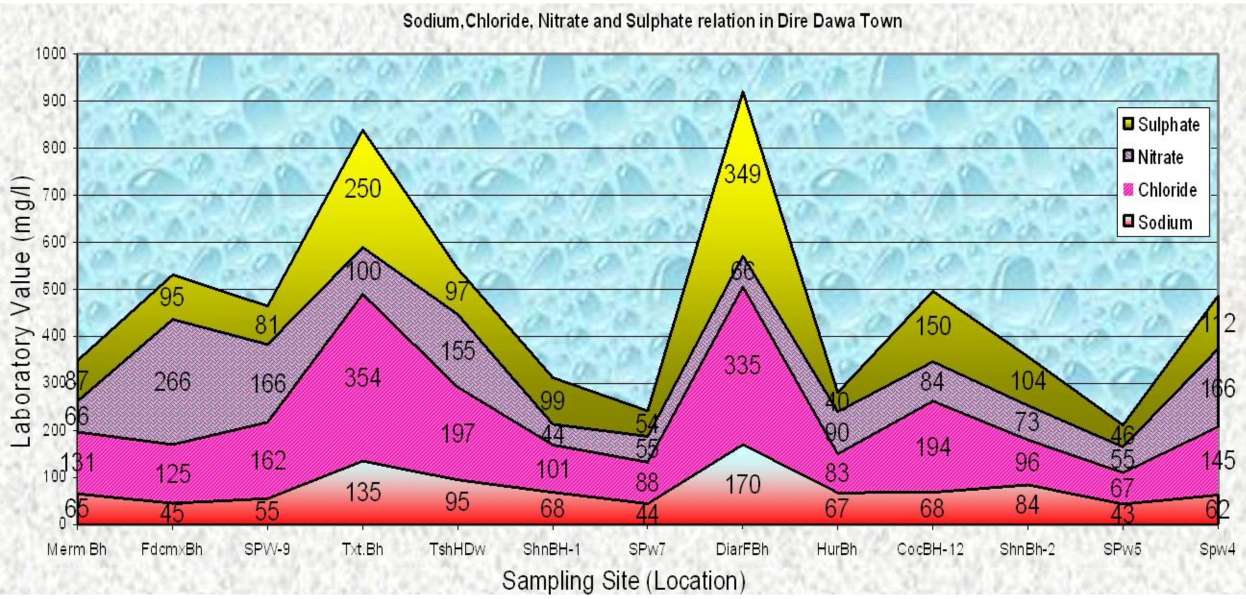

Fig 14 Sodium, Chloride, Nitrate & Sulphate relations in the Dire Dawa groundwater (mg/l)

The major anion values have increased at Txt.Bh and FBh bore holes as shown in (Fig 14) due to the influence of human factors where as the value the of the springs are much lower at Spw-5 and Spw-7 sampling stations (annex-I). Concentration of nitrate is high in the spring water. The potential source of nitrate in the spring sample is the use of ammonia, forest coverage and manure as fertilizers, the major acidifying process in the soil since; $\mathbf{NH^+_4 + 2O_2 \Rightarrow NO^-_3 + H^+ + H_2O}$. In general there is groundwater modification by human interference since anions are increasing and decreasing at the same time that clearly observed in the Fig.14.

From graphical presentation of chloride versus nitrate (Fig.15), chlorides (Cl^-) are positively correlated with nitrates (NO^-_3) with a correlation line of (NO^-_3 = 0.76Cl-15.7). Mathematically; the slope is 0.76 between chlorides & nitrates. The coefficient of correlation (R^2=0.6877) shown in the Fig.15 represents there is linear relationship between chlorides and nitrates (mg/l).

The mathematical formula for computing ***r*** is:

$$r = \frac{n\sum xy - (\sum x)(\sum y)}{\sqrt{n(\sum x^2) - (\sum x)^2}\sqrt{n(\sum y^2) - (\sum y)^2}}$$

where *n* is the number of pairs of data; x and y represent the value of chlorides and nitrates respectively.The data follow a linear pattern by using the line results in less error than using a simple arithmetic average. The coefficient of determination represents the percent of the data that is the closest to the line of best fit. In the case of Dire Dawa the value of R^2 = 0.6877, which means that nearly 69% of the total variation in chloride can be explained by the linear relationship between nitrate and chloride (as described by the regression equation).

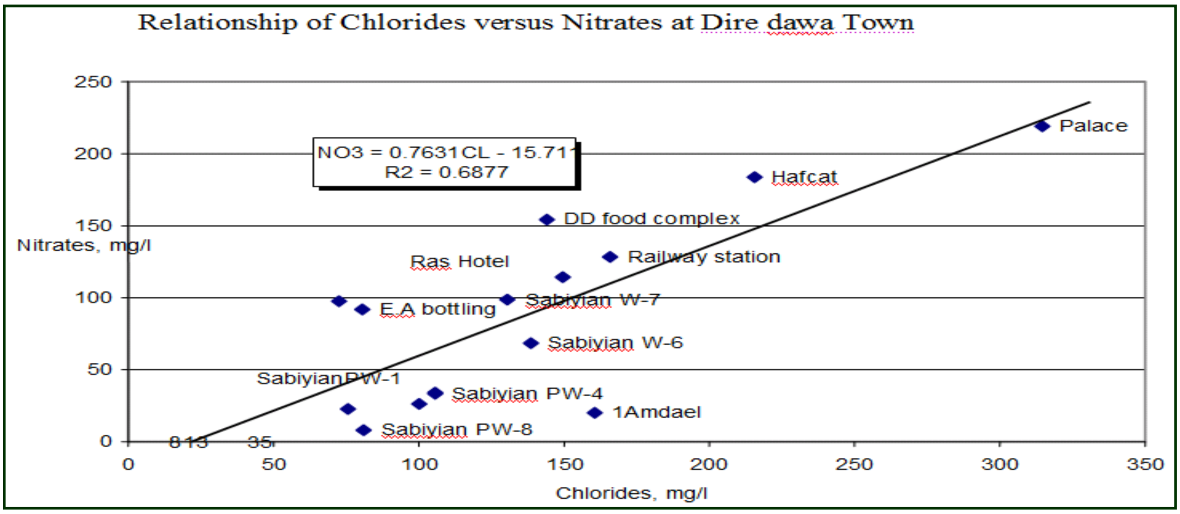

Fig .15 Chlorides v's Nitrates relation in the Dire Dawa condition (from WDDSE, 2004)

The graph (Fig.15) shows most of the shallow bore holes are located above the line i.e DD food complex and Ras hotel which have the nitrate values of 155mg/l and 188mg/l while most of the values chloride show less than 160mg/l below the line except Palace borehole at the pick value of 320mg/l. Nitrates are highly soluble and have more chance to be depleted through reduction and biochemical reaction in the system as shown from DD food complex to Sabiyan Pw-1 since chloride is non-reactive.

Mostly the source of the Na+ and NO_3- is derived from municipal wastewaters contain large amounts of organic wastes, so the wastewater will have a high ammonia concentration. Na^+ become depleted in the downstream flow as compared the borehole samples at different water points since part of Na^+ is sorbed by the sediment or phreatic aquifer in the geochemical processes. In general the concentration of the solute/contaminant is decreasing in relation along the flow distance and time from the point source. Sorption tends to cause contaminants to move more slowly than the groundwater, therefore the effects must be taken into consideration when calculating how far the contaminant has traveled in a given time period. Most of the inorganic contaminants liquid can be dissolved in water at a specified temperature and pH in the groundwater system.

5. Contaminant Transport and Conceptual Model

Modeling is very important in order to understand and conceptualize the field conditions of groundwater system by analyzing and simulating the physical and chemical parameters into the model. It is a complex process to model the subsurface groundwater system in connection with the contaminant transport in the aquifers. It requires detailed and valid data; defining the flow lines of groundwater in the aquifer, calculating the travel times of water along the flow lines and calculating the dispersion of solutes (Appelo, 2005). Contaminants transport is controlled by the physical, chemical, and biological processes in groundwater with various interacting processes, advection, dispersion and chemical reactions that influence the movement and fate of contaminants.

It is possible to develop a model from simple (Darcy's Law) to complex (finite method/3D) by defining all input parameter values and selected site characterization. The most important issue here is conceptualizing the geological and hydrogeological settings and also human inputs in the system. *No model is perfect for all situations*. A mathematical equation or computer generated model does not provide a unique solution to an environmental problem. It provides a scenario based on specific assumptions and specific input values. Varying certain input parameters can have a dramatic effect on the results of a model. Selecting proper boundary conditions and other parameters can be quite problematic. Any modeling effort should include a full written description of sensitivity analysis results and a written justification for any assumptions and input parameter values used other than model defaults (Steven A., 2001).

5.1 Groundwater flow and influence of production wells

The groundwater flow direction is controlled by many factors under subsurface condition. There are different types of complexity in the subsurface; faulting and bedding, slopes, the hydrological characteristics of the materials and locations of water all helps to define how the water will move into the subsurface system. In the case of Dire Dawa area, as it has observed from the groundwater contour map (Fig.16), there are two types of groundwater flow; local and regional. Locally, towards the well-field which is highly influenced by production wells and the regional groundwater flows towards the north direction that is similar to the surface flow.

Groundwater contour map can be produced by applying Surfer Golden software (refers, Fig.16); using the water point coordinates (x, y) and the groundwater elevation point at the z-dimension as shown at Annex-V. In some places the groundwater flow influenced by pumping well interference as it has observed on the map as a sort of cone of depression around the production wells. There are more than 100 functional and non-functional deep and shallow wells in the city. As we have observed from Fig.16 and Fig.17 the groundwater flow towards the north and the contour lines are influenced by the group of production wells. This made a chance that the residual time of groundwater flow to be decreased since the hydraulic head difference is increasing. This makes that the velocity of groundwater flow becomes too fast and the cone of depression further deeper and deeper that show in the Fig.16. On the other hand this makes accelerating the groundwater flow velocity and have a great chance that the contaminant easily join in the production well before matured evolution.

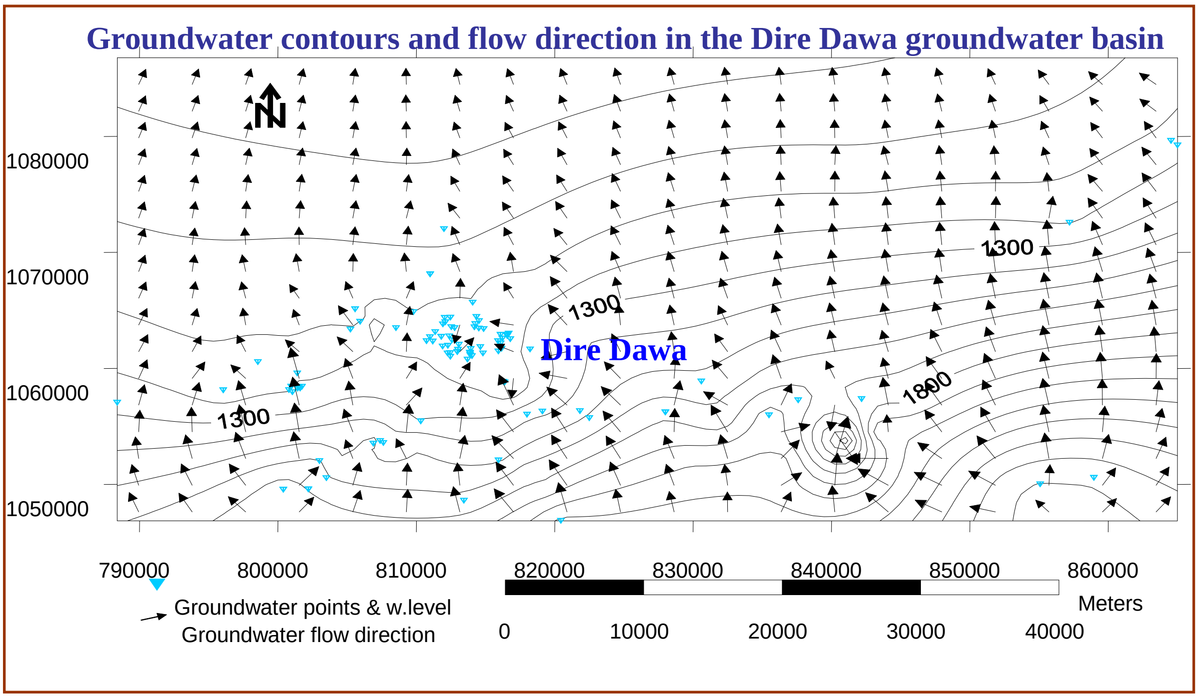

Fig.16 Groundwater contours and flow direction in Dire Dawa Area

Most of the wells concentrated in the inner part of the city and around the Sabiyan well-field. The unconfined shallow groundwater exposed for difference pollutant sources due to human interference as we have understood the water quality data from Tsehaye dug well. The water quality of FSP-5 (Fechass Spring) automatically modified downstream (Table.6) when we have traced the water quality data of TDW-1 (Tsehaye dug well) and FBh-12 (DD Food complex BH) within a depth of 15m-40m in the down town (Fig.17). Fig.17 has given very good background to develop and conceptual the ‘Box Model’. The flow path and water points have already interconnected to trace the groundwater quality and sources of modifier through geochemical evolution.

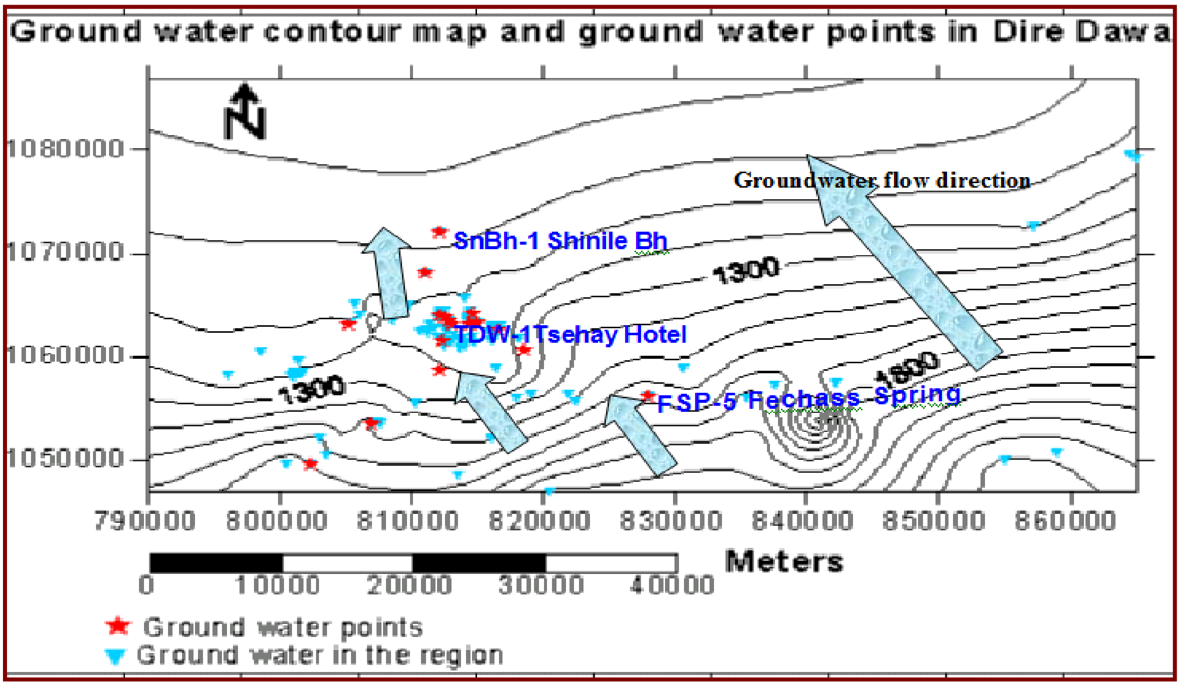

Fig.17 Groundwater contours and water points in the vicinity of Dire Dawa Area

Most of shallow wells are located in the inner part of the city having high population density (Fig.9) and a lot of industrial activities as shown from land use and urbanization map (Fig.8). The shallow wells are as deep as from 15m-40m at unconfined alluvial aquifer system owned by privates for drinking, agricultural and industrial activities. From water quality data, these wells are highly exposed for pollution since there is a municipal input source. Major anions like Nitrate (NO_3^-) and sodium, originates mainly from organic municipal sources in urban areas due to sewerage sources. The nitrate concentration is declining from the urbanized part towards the Shinile (SnBh-1) downstream of the study area as shown the from distribution map of nitrate in the basin (Fig.18).

5.2 Nitrate and zone of pluming in phreatic aquifer

Contaminants in groundwater move as a function of the soil porosity, the hydraulic gradient and permeability as well as hydrogeochemical processes. The contaminants will decrease in concentration because of such processes as filtration, sorption, various chemical processes, microbial degradation, time rate release of contaminants, and distance of travel (U.S. EPA, 1985). Mechanisms involved include filtration, sorption, chemical processes, microbiological decomposition and dilution depending on the type of pollutant and on the localized hydrogeologic situation (Todd, 1980). Contaminants might be faced with chemical reactions when transport through an aquifer, their flow velocity becomes less than groundwater flow. Such chemical reactions that slow movement of contaminants in an aquifer include precipitation, adsorption, ion exchange, and partitioning into organic matter or organic solvents (U.S. EPA, 1989a).

Nitrate does not have a conservative nature like chloride as it degrades under anaerobic condition by denitrification processes. High concentration nitrate is directly related to high population density (Fig.9) and industrial areas (Fig.8) in the urbanized part of city as it has observed from Fig.18. The plume is moving along the groundwater flow direction and decreasing from the core of the contaminated zone towards the downstream. At Sabiyain well field the pluming concentration of nitrate is decreasing at the range of 15-45mg/l due to low inputs and high travel time which exposed for denitification processes and reduction mechanisms. Some of the wells in the well field are located within the second and third the pluming zones which have 45-105 mg/l of nitrates (Fig.18).

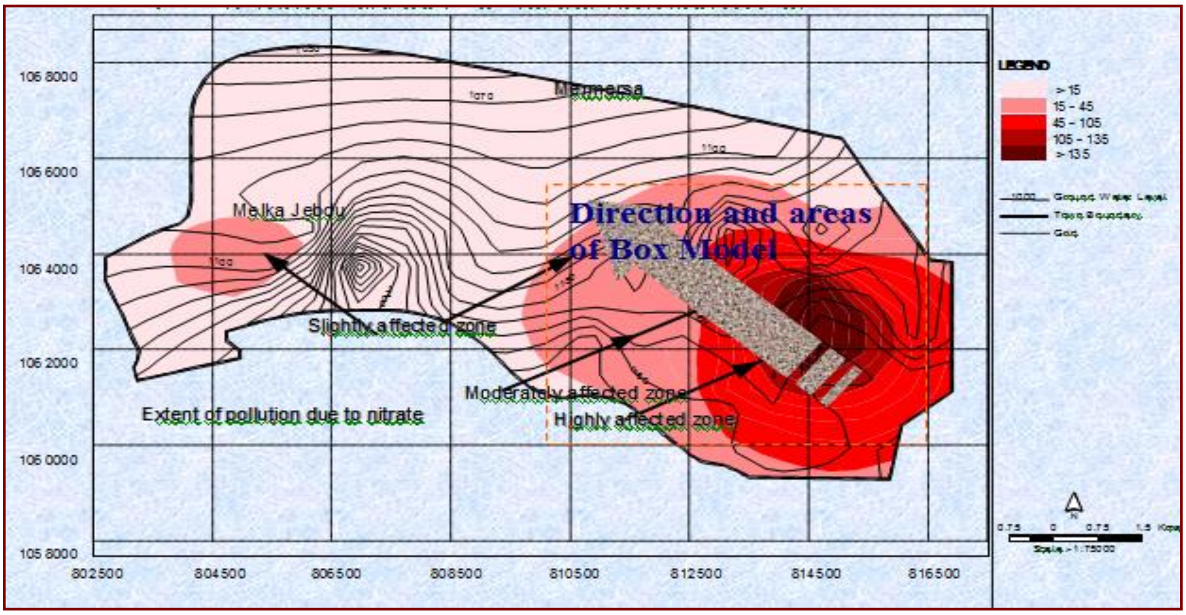

Fig. 18 The pluming zone of nitrate along groundwater flow direction in downstream of Dire Dawa

From the nitrate distribution map, at the centre of the city the groundwater is highly polluted by nitrate due to release of untreated wastes into the aquifer system. In particular, the water quality of alluvial aquifer is highly contaminated by human interferences. The box model conceptualized the core of the contaminated area towards at a distance of 2.5- 5 km radius downstream (Fig. 18).

Denitrification is the reduction of nitrate to N_2(g) by bacteria, through a complicated pathway involving intermediates like nitrite. It should be noted that denitrification is not a reversible reaction; there are no bacteria which are able to oxidize N2(g) to NO_3-. Dissimilatory nitrate reduction to NH_{4+} is also possible in groundwater systems but plays normally a subordinate role (Appolo, 2005). During nitrification, bacteria oxidize amines from organic matter to nitrite and nitrate. Despite the important effect of microbial kinetics on the nitrogen system, the equilibrium relationships must always be the first starting point.

5.3 Contaminant Transport in unconfined aquifer

There are two types of aquifer system in the Dire Dawa groundwater basin (WWDSE, 2004); the unconfined alluvial and the confined limestone and sandstone aquifer system. The upper unconfined aquifer is highly exposed for pollution as it shown from the water quality data. Contaminants have different physical and chemical property in order to trace their fate under different hydrodynamic system. On the other hand it is possible to predict the fate of chemicals during their transport in groundwater using different conceptual model by applying Darcy's law under homogeneous condition and mean value of hydraulic parameters.

In order to simplify the box model to conceptualize contaminant transport, it is easy to use the unconfined aquifer unit under homogeneous conditions. Most of the physical parameters can be estimated and taking the average values by referring the previous studies and assimilating the general hydrogeological settings of the study area. The study focused on nitrate (or chloride as conservative) and its nature in the unconfined aquifer system with homogeneous sediments that assume uniform porosity and permeability distribution in space.

5.3.1 Conceptual box model for simulating the nitrate plume

The box model predicts that the aquifer contains water of equal age at each depth, independent of location: the isochrones are horizontal. Predict the future or look into the past with an impressive line of advanced three dimensional groundwater flow and contaminant transport modeling According to Apelo (2005) water in the unsaturated zone percolates vertically downward along the maximal gradient of soil moisture potential, when relief is moderate. Solute/contaminant transport in the unsaturated aquifer is moving through slow flow and biodegradtion processes. A simple mass balance can give the rate of percolation at steady state:

$$\boldsymbol{v} = P/\,\varepsilon_w \longrightarrow \boldsymbol{v}_{H2O} = P/\boldsymbol{\varepsilon}_w$$

where P is the precipitation surplus (m/yr), and ε_w the water filled porosity.

The water velocity in the unsaturated zone by applying simple mass balance formula at steady state in a homogeneous sandy alluvial media is; $V_{H2O} = P/\varepsilon_{w,}$ where P is the precipitation. The annual precipitation in Dire Dawa is about 618mm per year. Assume the porosity (ε_w) filled by water is 0.3 in the alluvial sand in unsaturated zone. From WWDSE (2004) groundwater reserve calculation 30% (185mm/yr) of the annual precipitation is infiltrated in the groundwater system. Then the water velocity in the subsoil media is about 0.62m/yr. This value may vary from place to place even in unconfined aquifer system because the groundwater level is fluctuated from season to seasons and highly exploited by the residents. It is important to understand that the groundwater flow velocity increases with distance from the divider, since more precipitation must be discharged through the same thickness and also the effects on production wells.

In the unconfined alluvial aquifer and homogeneous system, to simulate the box model assume the porosity and permeability should be equal everywhere in the model area. To exercise this model we can take the three water point sites at different locality along groundwater flow direction. This conceptual model is more of assumption and integration by assimilating the physical and chemical parameters based on the available information rather than to reflect the reality since the hydrogeological setting is complex. From the spatial distribution of groundwater points, Tsehaye Dug Well (TDW-1) is located at the city centre as a source of leachate from the waste that percolating into the aquifer at the surface elevation of 1160m. The Sabyian well field and Shinile Bore hole (SnBh-1) are located at a distance of ≈2500m and 5000m (Fig.19) apart downstream from the city at 1160m and 1100m surface elevation respectively (Fig.17 & Fig.19).

This simple 'box model' method is can be used estimate the travel distance and time in order to predict pluming of contaminant transport in phreatic aquifer system. Contaminants have different conservative and non-conservative behaviors during the transport mode. Contaminant transport in the groundwater is moving through faster flow with dilution (dissolution) and geochemical/biogeochemical reaction (Appelo, 2005). From the chemical data analysis chloride and nitrate have similar trend on the contaminant flow map and graphical presentation. It is possible to conceptualize in the 'box model' as shown in Fig.19 for the transport of chloride or nitrate from the inner part of the city towards Sabiyan well field at the distance of (≈2500m). We assume that the values of hydraulic parameters (porosity. gradient and permeability) are constant everywhere and there is a point source of contaminants within 25m radius as a source area.

Groundwater flow at a given location depends on the permeability of the subsoil and hydraulic gradient. The specific discharge is given by Darcy's law as: v_D =-k(dh/dx) where v_D is specific discharge or Darcy velocity (m/day), K is permeability or hydraulic conductivity in m/day which has estimated about 1.4m/day (or ≈1.5 x 10^{-5} to 10^{-3} m/s) and (dh/dx) is the 1D - hydraulic gradient (Minalha, 2007).

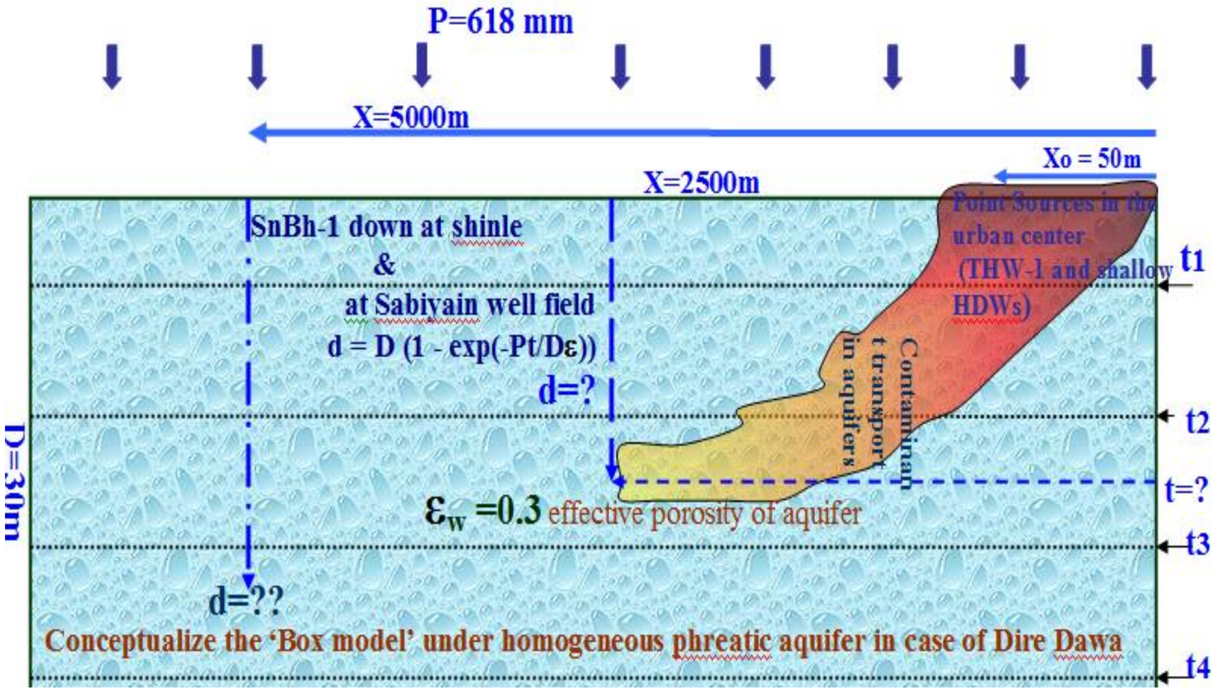

Fig.9 Conceptual box model under homogeneous phreatic aquifer and contaminant pluming

In the phreatic aquifer of 'box model', the point along the upper reach where water infiltrates, and depth in the aquifer are then related proportionally: **'$X/X_0 = D/(D - d)$',** where D is the thickness of the aquifer. Water infiltrated at a point x_0, upstream of x, is at a given time found at depth d in the aquifer. Above d flows water that infiltrated between point x_0 and x, below d flows water that infiltrated upstream of x_0.

In the homogeneous phreatic aquifer, the surplus precipitation P m/yr enters into the aquifer along its upper unit, so that Q = Px (m^2/yr) flows through the aquifer at point x**.** Using $v = Q/A\varepsilon_w$, the flow velocity at point x is: $v = dx/dt = PX/D\varepsilon_w$, where ε_w is effective porosity. From the given parameters the flow velocity of the aquifer ($V=dX/dt = PX/D\varepsilon_w$) where D is the thickness of the phreatic aquifer and ε_w where ($\varepsilon \approx 0.3$) is effective porosity. Note that thickness D has replaced surface area A, since we consider flow in a profile (per unit width of the aquifer).

From is simple mathematical formula; '$X/X_0 = D/(D - d)$' at D=30m (the phreatic aquifer) and X_0 is the waste site of 25m radius. $X_{(Sb=2500m)}$ and $X_{(Sn=5000m)}$ located downstream of the waste disposal site. The calculated value of d_{Sb} and d_{Sn} is about 28m and 29m respectively. From this result we understand that there is insignificant hydraulic gradient difference between X_{5000m} and X_{2500m}. See the general steps and mathematical formula from Darcy's law to box model below. By Definition, $Vv / V_T = n$ (ε_w) the soil porosity; Where V_T = total volume & Vv = void volume

Darcy's law ⟶ $V_D = -\,k\,(dh/dx)$ .... (1)

$Q = V_D\,.A = -\,k\,A\,(dh/dx)$

Pore water velocity $v_{H2O} = V_D\,/\varepsilon_w = -\,(k/\varepsilon_w)\bullet(dh/dx)$

average pore cross section $(A\bullet\,\varepsilon_w)$; $v_{H2O} = Q\,/\,A.\,\varepsilon_w$

The homogeneous phreatic aquifer

'Box model' ⟶ **'$X/X_0 = D/(D - d)$'** .... (2)

$V = Q\,/\,A.\,\varepsilon_w$ or $v = dx/dt = Px/D\varepsilon_w$

$\ln(D/(D - d)) = Pt/D\varepsilon_w$ or $d = D\,(1 - \exp(-Pt/D\varepsilon_w))$

Concentration of contam.in the aquifer (NO_3)

The average concentration at 'd' ⇨ $C = (C_0 d + C_i(D\text{-}d))/D$ .... (3)

If C_i=0, then: $C = C_0 d/D = C_0\,(1 - \mathbf{e}^{(-(Pt/D\varepsilon w)})$

For such a reactor, the **residence time** is defined as

Residual time in the aquifer ⇨ $\tau = V/Q = (D\varepsilon_w\,X)/PX = D\varepsilon_w\,/P$

Concentration at a time τ ⇨ $C = C_0\,(1 - \mathbf{e}^{(-t/\tau)})$

From flow transport of Appelo (2005) integration & substitution equation

From the above mathematical formula and derivative, the box model predicts lateral extent and the depth of the plume in phreatic aquifer system (unconfined alluvial deposits).

Integration of $v = dx/dt = PX/D\varepsilon_w$ gives, when water infiltrates at t= 0 at $X = X_0$

$$\ln(x/x0) = Pt/D\varepsilon_w \text{ or the distance X reached in time t: } X = X_0\, e^{(Pt/D\varepsilon w)}$$

We may also substitute the proportionality relationship $X/X_0 = D/(D - d)$, which yields:

$$\ln(D/(D - d)) = Pt/D\varepsilon_w \text{ or } d = D\,(1 - \exp(-Pt/D\varepsilon_w))$$

In the case of the study area, it is possible to predict the contaminants in shallow aquifer in particular chlorides (as non-reactive/conservative tracer) which have conservative nature (Fig.19). From conceptual box model we can calculate the flow velocity water from the source area of the contaminants till the Shinele and Sabian well-field respectively i.e $v = PX/D\varepsilon_w$

$$V_{Sn} = 30\%(618)mm*5000m\,/30m*0.3 = 0.185m/yr*5000m/9m=100m/yr$$

$$V_{at(Sn=5000m)} = 100m/yr \text{ where as } V_{at(Sb=2500m)} = 50m/yr$$

Accordingly the residual time of 't' is ⇨ $X = X_0 \exp(Pt/D\varepsilon_w)$

We may also substitute the proportionality relationship **$X/X_0 = D/(D - d)$**, which yields:

$$\text{time is } \ln X/X_0 = Pt/D\varepsilon_w;\ \ln 2500/25 = 4.6 = Pt/D\varepsilon_w$$

$$t_{Sb} = 4.6*30m*0.3/0.185m/yr=220yrs \text{ and } ⇨ t_{SnBh\text{-}1}=250yrs$$

The depth of the plume to at a distance of X_{2500m} can be calculated by the following formula,

$$d = D\,(1 - \exp(-Pt/D\varepsilon_w)) \text{ i.e at Sabian well field}$$

$$d_{Sb} = 30m\,(1 - \exp(-0.185*220/2500*0.3)) \approx 28m,$$

The calculated result show, there is no significant different between the depth of the Sabyian well field and Shinile bore holes along the downstream direction.

Aquifer as a chemical reactor: The concentration contaminants have changed in a certain depth and travel distance enhanced by dissolved substance and geochemical reaction. Assume a situation where the infiltrating water change from an initial concentration C_i at t<0 to C_0 at t=0. When the concentration front arrives at'd', the average concentration is:

$$\mathbf{C = (C_0 d + C_i (D\text{-}d))/D}$$

$$\text{If } C_i = 0\text{, then: } C = C_0\, d/D = C_0(1 - \exp(-Pt/D\varepsilon_w))$$

This function is similar to the "ideal mixed reactor" used in chemical engineering (Appelo, 2005). For such a reactor, the residence time is defined as,

$$\tau = V/Q = (D\varepsilon_w X)/PX = D\varepsilon_w/P$$

$$C = C_0(1 - \exp(-t/\tau))$$

It is possible to calculate the residence time and the depth of the contaminant along the flow direction in the subsurface system that the aquifer contains water of equal age at each depth, independent of location. The residence time and concentration of nitrate (C_i=155mg/l) at the aquifer depth of D=30m is defined as:

$$\tau = V/Q = (D\varepsilon_w X)/PX = D\varepsilon_w /P = 30m*0.3/0.185\ (m/yr) = 48yrs.$$

$$C= C_0 d/D = C_0\ (1 - \exp(-Pt/D\varepsilon_w)) = 155mg/l*.62 = 96mg/l.$$

The estimated time to reduce nitrate at 45mg/l level is expressed;

$$C= C_i\, e^{-t/\tau} \quad C/Ci = e^{-t/\tau}$$

$$\ln C/Ci = {}^{-}t/\tau \quad t=-\tau \ln 45/155=-48 *-1.2=60yrs;$$

From the above calculation, it demands more than 60 years in order to minimize (45mg/l) from the existing nitrate (155mg/l) concentration at the city centre assume the source inputs discontinued at the same time. This value is just to conceptualize the system; it does not present the real cases of Dire Dawa since some of the parameters are more of assumptions.

The physical environment is very warm and the biodegradation rate may be faster and the estimated time becomes shorter than the simulated value. For example the concentration of NO_3 (mg/l) become depleted at the depth of 'd_{Sn}' (44 mg/l) towards SnBh-1 compared with TDW-1 (155mg/l) from the centre since contaminants are moving through dilution (dissolution) and geochemical reaction in the groundwater with high reduction and denitrification processes.

The unconfined alluvial aquifer unit of Dire Dawa is composed of poorly sorted fluvial gravel, sandy and siltstones, mainly formed through fluvial processes. So the residence time of the contaminants may be estimated less than the calculated value. The residence time becomes 24 years if we apply different artificial mechanisms in the system since there are a lot of factors which influence the route and excluded in the model. In general the box model is more sensitive for hydraulic conductivity than the hydraulic gradients and infilitration rate of precipitation.There are many factors in the study area that posatively or negatively influence the model result more described in uncertainty part.

5.3.2 Contaminant transport

There are complex factors that control the movement of contaminants in groundwater and soil in order to predict the movement and extent of the plumes. Processes such as hydrodynamic dispersion affect all contaminants equally, while sorption, chemical processes, and degradation may affect various contaminants at different rates (U.S. EPA, 1985). The retardation factor, R (calculated) will be 1.0, if the solute is non-reactive and moves with the groundwater. If R is greater than 1.0, the average velocity of the solute is less than the velocity of the ground water flow, and the dispersion of the solute is reduced. Contaminants with lower retardation factors are transported greater distances over a given time than contaminants with larger retardation factors (U.S. EPA, 1989a).

There are lot of controlling factors for natural attenuation of contaminants in the soil and groundwater as it is shown in Fig. 20. There are more than 65, 000 tones municipal wastes of Dire Dawa simply released into the unconfined aquifer per year. The contaminants in the aquifer have different evolution stages and captured by different electron acceptors. The most important processes that affecting the attenuation of contaminants shown (Fig.20); volatilization/evaporation, advection, sorption (absorption & adsorption) and biodegradation (aerobic & anaerobic). Most of these processes are dependent on the aquifer and/or contaminant properties.

From the water sample result analysis (part-4), Sodium (Na) becomes retarded by ionic exchange and sorption activities. Mostly the source of the Na^+ and NO_3 is derived from municipal sewerage (pit latrines) in the urban centre. Na^+ becomes retarded in the downstream flow velocity as a result of sorption by the sediment or aquifer in the geochemical processes. Relatively Ca^{2+} and Mg^{2+} also retarded in the aquifer. The water sample results show that there is clear redox and sorption process going between water sample TDW-1 (from the inner) and SnBh-1 in the downstream. The concentration of the solute/contaminant is decreasing along the flow distance comparing with from the point source. Sorption tends to cause contaminants to move more slowly than the groundwater, therefore the effects must be taken into account when calculating how far the contaminant has traveled in a given time period.

Nitrates are scarcely soluble in water and mobile in the saturated meida than others as shown in (Fig.20) since the only way for in situ nitrate removal from groundwater is by reduction. Denitrification is the reduction of nitrate to nitrogen gas, and requires anoxic conditions and an organic-carbon source. The organic carbon source can be found in natural soils or within the effluent of anthropogenic sources. At the groundwater table the O_2 concentration is already depleted. Denitrification occurs when oxygen levels are depleted and nitrate becomes the primary oxygen source for microorganisms. Fig.20 has shown that the mode of contaminant transport at different redox zonation due to municipal waste pollutants in unsaturated and saturated zones cases like Dire Dawa.

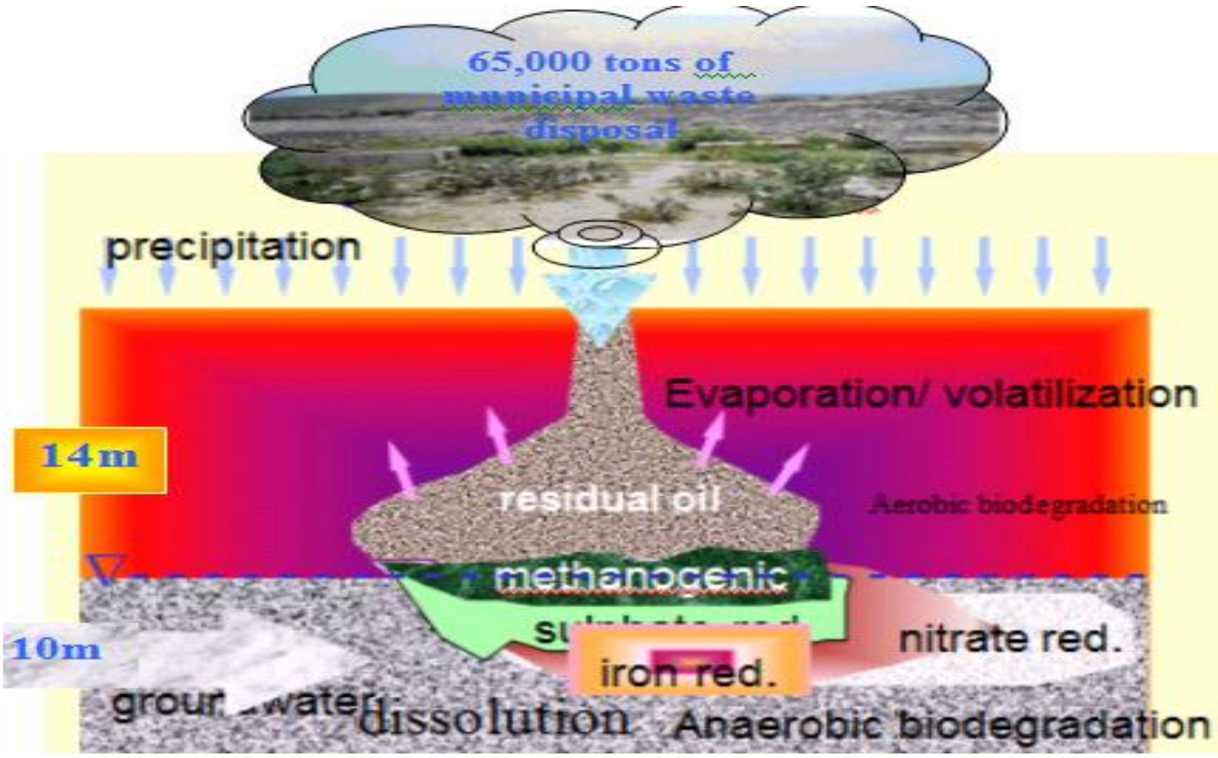

Fig.20 Mode of contaminants transport and natural attenuation at different aquifer media (modified from GEO4160, 2008, UiO)

Contaminants originated from human activities and leachates into subsurface environment through waste disposal practices; septic tanks and sewage discharges. Contaminants are scarcely soluble in water that have a strong tendency to bind by aquifers or to be retarded (to move much more slowly than the rate groundwater flows). Many contaminants readily sorb to immobile aquifer media and therefore are considered to be virtually immobile in the subsurface and to present little danger to groundwater supplies (Appelo, 2005).

From the above conceptual physical environment it is possible to assimilate the contaminant transport in the phreatic aquifer groundwater of Dire Dawa. From the urbanization map one can assume that the core of the disposal site (leachate) is located in inner part of the city within 25m radius. The hydraulic parameters are variable but we can take average values i.e hydraulic conductivity (K) from 1.5 x 10^{-5} to 10^{-3} m/s (ave≈$9.55e^{-04}$), hydraulic gradient (0.05 to 0.08) and effective porosity of the layer is 0.3. The most interesting area for the contaminant transport calculation is the distance between the most urbanized part of the city to the well-field (Sabyian=2.5km).

We can assume that contaminants are non-reactive, solute does not sorb by sediment grains then velocity of contaminant is similar with the velocity of water in the groundwater (i.e $V_c = V_{H2O}$). In relation with hydraulic gradient, the specific discharge is given by Darcy's law as: $V_D = -k(dh/dx)$, Where V_D is specific discharge or Darcy velocity (m/day), k is permeability or hydraulic conductivity (m/day), and (dh/dx) is the 1D - hydraulic gradient.

The Darcy velocity is defined a.s specific discharge per unit area of the aquifer. However, only the pore space contributes to water flow, so that the actual velocity of water movement through the pores must be larger. The actual velocity is known as pore water flow velocity. When the porosity is a fraction n, the pore water velocity is: $V = V_D /n = - (k/n)\bullet (dh/dx)$. From this background information, the expected travel distance of the plumes is observed in the Fig.21 by applying simple mathematical formula.

$$V = V_D /n = - (k/n) \times (dh/dx)$$

The mean actual velocity is, $V= Ki/n = (9.55e^{-04} * 0.065)/ 0.3$ which is about

$$\Rightarrow 2.1e\text{-}^{04} \text{m/s (0.3m/day or } \mathbf{110m}\text{/year).}$$

This actual velocity of water (solute) may vary from 25m/yr to 210 m/y if we use the mean range values of hydraulic conductivity k (m/day) and hydraulic gradient (dh/dx) respectively in the study area of Dire Dawa.

According to the study of Klonowski et al. (2005), which was conducted under '*Natural gradient experiment on transport of jet fuel derived hydrocarbons in an unconfined sandy aquifer'* at the international Oslo airport, the value of groundwater velocity varies from 0.25 to 1 m/day. This value gives some ranges from 90 to 360 m/year for the transport of organic contaminants depending on the hydraulic parameters and contaminant behaviours. The V_c- velocity of contaminants has equal chance to transport with the V_{H2O} - velocity of water on the assumption of non-reactive nature.

On the bases of the groundwater velocity in Gardermoen from 0.25 to 1 m/day, this gives 90 to 360 m/year by applying the distance travel formula **'$X_c=V_c.t = (V_{H2O}).t$'.** This travel distance is mainly depending on the aquifer hydraulic parameters (K, dh/dl, n) and the behaviour of the contaminants. It is possible to exercise (contaminant transport) in this range value for non-organic contaminants (Chloride or nitrate) under the similar hydrogeological settings and hydraulic parameters as shown at Fig.21 (in Dire Dawa).

In Dire Dawa, more than 65,000 tones of municipal wastes dispose on the unconfined aquifer unit per year (Fig.20). Some of the waste disseminated and some of them transported by different mechanisms in the unsaturated and saturated zone respectively. Based on the above background, it is possible to estimate the travel distance and residence time of the contaminant in saturated media of Dire Dawa basin (Fig.21). In this calculation the hydraulic parameters (K, dh/dl) are very critical in the Dire Dawa situation. The result varies from **25m to 210m** per year by taking the range values of hydraulic conductivity and hydraulic gradients respectively. Fig.21 shows as a conceptual model of the groundwater flow and contaminants transport integrated with photo from the Dire Dawa disposal site.

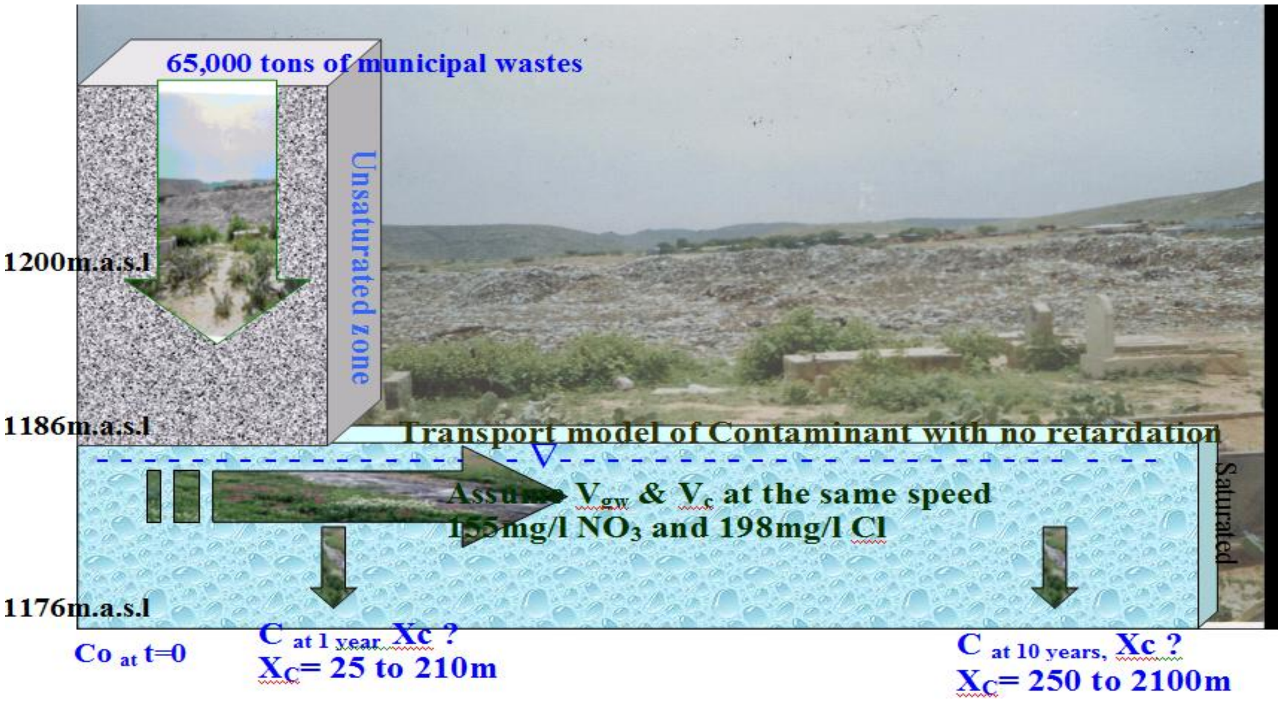

Fig.21 Transport of contaminants in the aquifer with non-reaction simulated in Dire Dawa

The hydrogeological settings and hydraulic parameters (K, dh/dl, n) of the Gardermoen area has similar hydrogeology complex with Dire Dawa basin because the alluvial aquifer in Dire Dawa composed of cobbly gravel and coarse sands as well as interbeded layers of the gravely, coarse sands and fine, silty sands formed through fluvial deposits. If we compare the calculated result of the groundwater velocity (110m/year) and other hydraulic parameters in Dire Dawa, the values are similar within the ranges Klonowski (2005) experiment study on transport at the Gardermoen area.

Based on the above assumption the travel distance of the plume having non-reactive, 155 mg/l nitrate and 198 mg/l chloride concentration is presented in Fig.21. In Gardermoen, it takes 10 years to travel 900m to 3600m. This distance lies within the Dire Dawa to Sabyian range that is about (2500m). So it takes **12years to 100years** to travel the contaminants to reach the Sabyian well field of 2.5 km in Dire Dawa. At the same time it requires up to 100years to clean up contaminated phreatic aquifer assume the source of leachate should be disconnected. Comparing the box model, the plume travel time is about 24 to 60 years at a distance of 2500m with some sort of modification and assumptions. Nitrate has different chemical processes at different media but pluming has still expanded to 2.5km distance from the sources area. There are many non-point sources in-between the main source (leachate) and the well field that helps to amplify the pluming zone.

5.4 Result and discussion

Existing Situation and Pollutant Sources: In the study area, the main geological formations and outcrops are pre-Cambrian rocks, the Jurassic Adigrat sandstone and Hamanalei limestone, the Cretaceous upper sandstones, Tertiary basalts and Quaternary alluvial deposits. The groundwater occurrence and distribution in the basin is mainly a function of the geological formations, geomorphology and tectonic activities. The alluvial aquifers are mainly developed in the downstream of Dire Dawa basin. The unconfined aquifer unit in the alluvial deposits is the main interest area to exercise the study objective(s). The occurrence of groundwater in this formation is limited along the alluvial fans and river channel deposits. The thickness of the alluvial sediment on average varies mainly from 15 to 50 meters. The ground water depth varies in the alluvial sediments from 5 to 45 meters. The transmissivity of the alluvial formation is variable from 8 to 700 m^2/day, (pumping test result). On average the hydraulic conductivity is from 9.55 x 10^{-4}m/s at the aquifer thickness of 20m within the hydraulic gradient (0.05 to 0.08) and porosity the layer is 0.3. These values mostly applied for box model and contaminant transport prediction.

In Dire Dawa the potential evapotaranspiration (PET) is much higher than the actual evapotranspriration (AET). The annual precipitation in Dire Dawa is about 618mm per year. From groundwater reserve calculation 30% (185mm/yr) of the annual precipitation is infiltrated in the groundwater system. A precipitation surplus of P which infiltrates into the aquifer is 0.185 m/yr. There is excessive pumping and the groundwater has been depleted because the recharge estimation is about 300-370 l/s but the actual abstraction is 400m/l. The recharge estimation is not reflected the actual production either there should be some sort of trans-boundary groundwater sources contributing for the Dire Dawa groundwater basin or some error in order to balance recharge-discharge conditions.

The land use system Dire Dawa is mixed. All the urban activities are going on together. The city centre is highly populated around 350-500 per hectare (above the normal standard) with poor urban facilities. The rapid urbanization and lack of master plan implementation strategy are the main causes of pollution. The city has weak waste management mechanisms. The main sources of pollution are multiple point sources of pit latrines, septic tanks and linear source pollution of industrial and domestic waste disposal. Annually, about 10,000 m^3 of solid wastes and 65,000 tones of human excreta are simply released into the surrounding environment without any pre-treatment mechanisms. There is no 3R (Recycle – Reduce – Reuse) waste management principles. Domestic and industrial wastes are the main sources of pollution.These all urban activities directly or indirectly contribute for the surface and subsurface environmental pollution.

Results of chemical analysis: The physical environment and the hydrogeological settings contribute for change of water quality in the study area. Mostly springs originated at the escarpment zone from the contacts and fractures of the limestone-sandstone units. The water chemistry of escarpment zone is dominantly carbonate and bicarbonates type as a result of dissolution of carbonate rocks and silicate weathering processes. The major sources of anions like sulphate, and chloride are sedimentary origin of gypsum and halite.

There are many factors for change of water types; the geochemical evolution and water-rock interaction are playing important role. The residence time and sources of recharge are other factors which control water type with the activity of pH and the dissolution processes. The water quality of alluvial aquifer is highly modified as compared to water from upstream springs. There is no intensive agriculture in the region. The sources of nitrates, chlorides, sulphates and sodium modification of the groundwater in the study area is mainly influenced by human interference especially hand dug wells that are near to residential areas. The water types from upstream are mainly Ca-HCO_3 and Ca-Mg-HCO_3 but the water at downstream (Dire Dawa area) is changed by domestic activities to Ca-HCO_3-Cl, Ca-Na-HCO_3-Cl/NO_3, Ca-Mg-HCO_3-Cl and Na-Ca-HCO_3-SO_4. The most possible source of nitrate in the groundwater is pollution from the inappropriate wastewater collection and disposal system of city which is directly connected with the land use system and urbanization trends of Dire Dawa. The degradation of groundwater quality is also escalating by point source contamination such as septic tanks, pit latrines and industrial effluents.

Results of box model: Modeling is very important in order to understand and conceptualize the field conditions. But the hydrogeological setting of Dire Dawa and contaminant behaviour in groundwater system is very complex to simulate the hydraulic parameters into the model. Contaminants transport is also controlled by various mechanisms that influence the movement and fate of contaminants. Box model is important to assess the flow direction, solute travel time and also characterize the contaminated area (pluming zone) at a certain distance-depth by using simple manual calculation.

In the study area the groundwater flow is mainly towards the north direction that is parallel to the surface flow. The group of production wells and excessively pumping is highly affecting the local groundwater flow. This excessive pumping rate has depleted the aquifer and makes a chance the residual time of groundwater flow to be decreased since the hydraulic head difference is increasing. On the other hand this makes accelerating the groundwater flow velocity that the contaminants easily join in the production well system before matured evolution. The high concentration plume is flowing along the groundwater flow direction and decreasing in concentrations from the urbanized contaminated zone towards the downstream groundwater basin.

Applying simple mass balance formula at steady state in a homogeneous phreatic aquifer is critical to conceptualize the box model and contaminant transport in the Dire Dawa downstream. Most of the physical parameters used in the model were estimations and the average values by referring the previous studies and assimilating the general hydrogeological settings. Assuming the unconfined alluvial is homogeneous sediments that has the porosity and permeability are equal everywhere. Three water point sites (Tsehaye hand dug well (TDW-1), Sabyian well field and Shinile bore hole (SnBh-1)) considered in the box model at different localities along the groundwater flow direction.

From the chemical data analysis chlorides and nitrates (as non-reactive tracer) have similar trend on the contaminant flow map and graphical presentation to exercise the box model and predict the pluming zone. The calculated flow velocity is 50m/yr to move towards Sabiyan from the inner part of the city at the distance of (≈2500m) while the residual time based on 'box model,canculation is about 220yrs. These values are the results of box model by assuming that the values of hydraulic parameters (porosity. gradient and permeability) are constant everywhere and a point source of contaminants within 25m radius in the city. From this simple mathematical formula; '**X/X0 = D/(D - d)**' at D=30m the depth of contaminant at the localities of $X_{(Sn=5000m)}$ and $X_{(Sb=2500m)}$ the values of 'd_{Sn} and d_{Sb} are 29m and 28m respectively. From this result we can estimate that the pluming has insignificant hydraulic gradient difference between $X_{(Sn=5000m)}$ and $X_{(Sb=2500m)}$.

In order to reduce the concentration of nitrate from 155mg/l to bring down at the National drinking water limit of Ethiopia (=45mg/l); it has required more than 60 years by discontinued the source inputs at the same time. But by changing some values, for example at a depth of D = 20m, ε_w=0.3 and if P=0.3m/yr by applying artificial recharge in the aquifer system the residence time in the aquifer will become 24 years. This result shows that precipitation surplus highly influence the residence time of the contaminants and sensitive to the model.

Contaminant transport: The most interesting area for the contaminant transport calculation is the distance between from the most urbanized part of the city to the well field (Sabyian=2.5km). From the urbanization map, one has assumed that the core of the disposal site (leachate area) is located in inner part of the city within 25m radius. The groundwater velocity (V_{Sb}) from the box model calculation is 50m/yr (≈5.5 x10^{-4} m/s). The result's of box model has similar nature with the contaminant transport because the hydraulic parameters are similar and applied basic Darcy's law. The velocity of contaminant is similar with the velocity groundwater assuming that no-reactive nature of the contaminants.

The expected travel distance of the plume is 2500m (approximately from city centre to the Sabyian well field) with constant concentration. The mean actual velocity by applying the Darcy's formula (V=Ki/n = (0.000955 *0.065)/ 0.3 is about 0.298m/day (110m/year). This result is similar within the study of Klonowski (2005) range values from 90 to 360 m/year for *natural gradient experiment transport* of organic contaminants. The hydrogeological settings and hydraulic parameters (K, dh/dl, n) of Gardermoen area are similar with alluvial sediment composition of Dire Dawa area.

The travel distance of the plume having non-reactive concentration will take 250m to 2100m within 12 to 100 years time. These distance values are within the waste site (leachate) to Sabyian well-field distance range. Depending on hydraulic parameters, on average it takes more than 15 years the contaminants to travel and break into the Sabyian well field. At the same time it requires up to 100years to clean up contaminated phreatic aquifer assume the source of leachate should be disconnected. Comparing the box model, the plume travel time is about 24 to 60 years at a distance of 2500m with some sort of modification and assumptions. There are many non-point sources in-between the main source (leachate) and the well field that helps to amplify the pluming zone.

Actually the plume of nitrate is more mobile and soluble in saturated media. It may be removed and degraded from groundwater by reduction and availability of organic matters through anaerobic biodegradation processes. Sodium becomes depleted in the groundwater system of Dire Dawa mainly solubility nature and sorption activities in the aquifer. Mostly the source of the Na^+ and NO_3^- is derived from municipal sewerage (pit latrines) sources in the urban centre. In general the concentration of the solute/contaminant is decreasing in along the flow path and captured by different electron acceptors from its point sources. Major cations-anions depleted in the downstream basin by geochemical processes as we have observed from the groundwater evolution.

Model uncertainties: In the study area there are many input factors that make a variation on the output of a mathematical model result directly or indirectly. Most hydraulic parameters are more sensitivity in box model and contaminant transport calculation that can amplify model results. The most important factors that posatively or negatively contribute for groundwater flow and contaminats transport model are:

- hydraulic conductivity and hydraulic gradient
- inflitration rate of surplus precipitation
- built up area the city (≈50% built up area from 8,000ha)
- thickness of aquifer and homogeneity
- arfificial recharge from human sources (amount of leachates)
- floods and intermittent streams sink along sandy river channel
- Non-point pollutant sources out of the main pont sources(25m radius)

All the above parameters and indicators are important factors that determine the model result but most of the parameters are estimated and simulated from the measured data in order to conceptualize the hydrogeochemical dynamic system. These issues are not enough to address the uncertainty in model; it depends on the scale of the study. This type of approach may be useful in some places to realize the actual environment based on the available data still it has some limitations due to the complexity of nature.

6. Conclusions and Recommendations

6.1 Conclusions

Groundwater resources are under increasing threat from growing demands, wasteful use, urbanization and contamination. To face the challenge, scientific studies and proper utilization plan are needed. A key to the management of groundwater is the ability to model the movement of fluids and contaminants in the subsurface. The purpose of this study is to formulate groundwater flow and contaminant transport model that can provide preliminary information for proper groundwater resource utilization and management in the Dire Dawa area.

The study has also tried to conceptualize the groundwater evolution in the Dire Dawa area by considering the hydrogeological settings and influence of anthropogenic activities. The geology and aquifer units are quite complex, so it is hard to develop modeling concepts and present the real situation of the area. The water chemistry results show a mixed type since the geological formation is complex with contributions both from natural processes and anthropogenic sources. The groundwater quality is modified by anthropogenic factors and natural groundwater evolution along the groundwater flow path. In general the water quality is hard and mostly carbonates water types at upstream and more modified in the downstream basin especially in the shallow wells with high chlorides and nitrates due to contamination of the aquifer by human activities.

The water quality data provide enough background to identify pollutant sources and to conceptualize the contaminated aquifer zone by applying simple box model and contaminant transport. Contaminants have different attenuation and degradation rate in the subsurface conditions in order to identify the pluming zone under Dire Dawa hydrogeological settings. The alluvial plain aquifer in Dire Dawa area contains unconsolidated sediment deposited by fluvial processes that facilitated the groundwater pollution.

Major cations-anions have been depeleted in the downstream basin by geochemical processes. There are human factors which have enhanced or modified the hydrochemical processes in the groundwater system as we have observed in the groundwater evolution. From the conceptual model, it is possible to realize the geochemical evolution from the rain to the spring water via urban environment towards the downstream basin. All these processes show that there is the availability of electron acceptors and electron donors between the upstream and downstream in the aquifer system to facilitate anion-exchange and contaminant degradation.

6.2 Recommendations

In Dire Dawa, urbanization is a major challenge for the city development. There is continuing rural-urban migration due to 'pushing-pulling' factors. There is no enough urban facility, lack of integrated waste management and regulatory body. It is challenging for next generation to clean-up the contaminated aquifer. So integrated waste management strategy and proper groundwater management should be implmented for sustainable development of the city.

It is possible to improve the model by defining certain parameters and clarifying uncertainties that contribute to model. The contaminant transport model is based on assumption and simplifications. This part could be improved even in a simplified way with additional detailed hydrogeological parameters

The model is very sensitive for hydraulic conductively and recharge (surplus precipitation). But on the aquifer reserve calculation, the estimation of recharge and discharge is in imbalance, it needs more analysis. The contribution of artificial recharge should also be evaluated, as groundwater recharge from wastewater disposal in the upper aquifer will be active.

The study area is very interesting to apply and develop different modeling techniques for the future. The degradation rate of contaminants in the aquifer should be investigated by applying appropriate modeling and software techniques, and not at least kinetic data.

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List of Annexes

Annex-I. Water sample result from Ethiopia Geological Survey laboratory (mg/l) from Dire Dawa area, Date 9/16/2003 and University of Avignon (France) water laboratory.

Field NO.	PH	EC(us/cm)	Na	K	Ca	Mg	HCO3	Cl	SO4	CO2	F.	NO3	H2Sio3
BH-1	7,21	910	38	1,5	100	38	388	47	101	42	0,35	10	30
DSP_1	7,12	2171	130	2,7	160	70	449	262	234	59	0,34	44	29
FSP-5	7,0	1059	64	0,9	128	23	415	91	40	47	0,62	66	48
MBh-10	7,86	1266	65	1,4	132	50	437	131	87	14	0,47	66	42
FBh-12	7,13	1696	45	1,2	183	48	344	125	95	45	0,51	266	43
SBh-9	7,12	1620	55	1,4	171	43	372	162	81	44	0,49	166	38
TBh-3	7,11	2425	135	3,2	240	65	403	354	250	50	0,39	100	40
MBh-1	7,15	952	36	1,2	110	39	443	57	64	52	0,58	22	38
TDW-1	6,78	1670	95	4,9	168	55	508	197	97	122	0,61	155	43
SnBh-1	7,3	1180	68	1,9	118	48	462	101	99	40	0,66	44	49
MSP-3	7,27	757	12	1,8	111	27	445	17	19	39	0,25	17	16
SBh-1	7,09	1062	44	1,2	133	33	427	88	54	55	0,49	55	35
DBh-13	7,04	2512	170	2,3	238	68	438	335	349	63	0,43	66	41
LSP-6	6,98	1157	60	2,2	143	30	437	120	63	67	0,47	33	29
HBH-1	6,79	1384	67	7,5	123	37		83	40		0,1	90	86,3
DB-13	6,55	2872	26	4,7	126	26		50	35			153	95,8
CBH-12	6,98	1312	68	4,7	164	52		194	150		0,6	84	95,8
SnBh-2	7,06	1528	84	4,3	107	59		96	104		0,1	73	118,2
SBh-4(Pw-4)	6,68	1358	43	3	108	31		67	46			55	76,7
SBh-7(PW-7)	7,18	1945	62	5,2	127	44,5		145	112			166	82,1
DDRn-2-Rn			1,26	2,6	14	1		3,33	13			15	

TBh-3:Textile cotton Bh	MBh-1:Melka Jebdu Bh
SBh-1:Sabiyan Bh-PW-1	FSP-5 :Fechass spring
TDS-1:Tsehaye hotel HDW	DSP-1:Dujuma Spring
DBh-13:Dairy processing Bh	MSP-3: Muluke spring
FBh-12:DD Food complex BH	LSP_6:Legehare Spring
SnBh-1: Shinile town Bh	HBh-1:Hurso militry BH
BH-12 : Cocac Factory Bh	MBh-10:Memerssa Bh
DDRn-2-Rain	SBh-9:Sabiyan Bh-PW-9

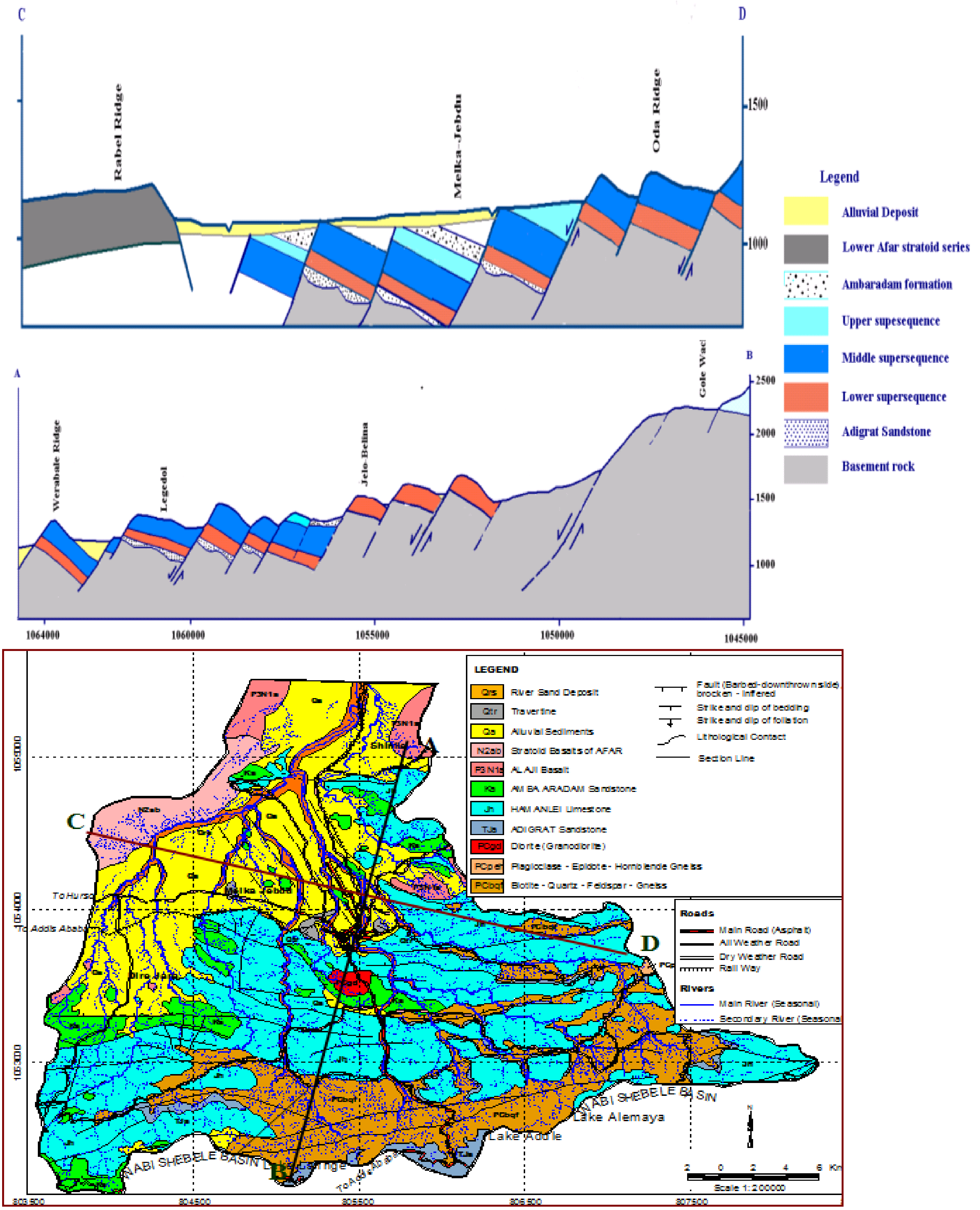
Annex-II. Mean monthly values of Dire Dawa Meteorological element (1972-2002)

	Jan.	Feb.	Mar	Apr	May	Jun	Jul	Aug.	Sep	Oct	Nov	Dec	Yearly mean
Max. Temp.	28.2	29.9	30.2	31.7	33.6	34.8	33.3	32.6	31.4	32.0	30.2	28.6	31.5^0c
Min. Temp.	15.3	16.6	19.2	20.5	21.6	22.6	21.1	20.6	20.9	18.9	15.9	15	19.0^0c
Relative humidity	39.3	42.5	44.4	47.5	35.2	30.0	41.4	40.8	34.6	27.6	29.6	29.9	41.4%
Sun Shine(hr)	8.8	8.0	7.8	7.4	8.4	8.1	7.5	8.0	7.7	8.3	9.4	9.3	
Evaporation (mm)	217.6	199.8	283	245.7	283	323	293.8	283	266.8	283	242.2	221.3	(open water)
Wind Speed (m/sec)	4.2	3.8	4.4	4.6	4.1	5.5	5.6	5.1	4.2	4.2	4.2	3.6	4.5m/sec
Rainfall (mm)	20.7	21.6	84.5	68.3	45.3	20.6	91.8	146.	85.3	32.2	12.9	11.1	618

- N. B. Taken from WWDSE (2004) Climatology and Hydrology Report.

Annex -III Aquifers type and their productivity in DDAC (WWDSE, 2004)

Aquifer	Aerial extent	Type of aquifer	Hydrodynamic parameters						Productivity of aquifer
			Yield l/s		*Specific capacity l/s/m*		*Transmissivity m2/day*		
			Range	Mean	Range	Mean	range	H.1mean	
Alluvial sediments	Extensive	Intergranular , unconfined	1.17-7.59	2.06	0.06-5.50	0.55	0.9 – 712.8	Avg. 69.1 Harmonic mean= 7.1	Moderate
Basalts	Localized	Fractured, unconfined	0.0 – 1.0	0.50	0.0 – 0.01	0.005	0.0 –5.72	Avg. 1.91	Very Low
Sandstones and lime stones	Extensive	Fractured, confined	3.4 – 45.4	20.45	0.14 – 67.3	7.0	29 - 5512	Mean=1404 Harmonic mean =243.8	High
Metamorphic	Localized	Fractured, unconfined	From statistical analysis of springs yield Q<<1 liter per second						Extremely low



Annex-IV Geological x-section and Stratigraphy of the Dire Dawa Area by Miruts (2003)

Annex-V Groundwater points and water level in the Dire Dawa Catchment area

No	**Well Index**	**Local Name**	**X-Coo**	**Y-Coo**	**Ground Elvation (m)**	**GWL(m)**	**Well Depth (m)**	**SWL (m)**
1	BH-01	Armakule	844564	1086779	932	900		
3	BH-04	Cheremiti-#2	864535	1079607	1152	1130.58	101	21.42
4	BH-09	Melka Jebdu-3	805167	1063299	1131	1108	106	23
5	BH-52	Rail way statio	813936	1061662	1180	1150.23	62	29.77
6	BH-54	Textile-1(old)	816702	1062643	1192	1166.9	45.7	25.1
7	BH-07	D/Dawa food com	814520	1063426	1177	1147	115	30
8	BH-15	Hafcat #2	814941	1063539	1167	1167	56	
10	BH-08	Melka Jebdu #2	805241	1063341	1141	1111.5	95.6	29.5
11	BH-12	Palace	814172	1061499	1202	1167.9	48.8	34.1
12	BH-14	Hafcat #1	814865	1063384	1168	1168	86	
13	BH-26	Dire Jara W-1	801010	1058803	1230	1180.4	163.5	49.6
14	BH-27	Dire Jara W-2	801394	1059555	1210	1121.78	161.5	88.22
15	BH-28	Dire Jara W-3	801437	1058786	1229	1229	172	
16	BH-29	Dire Jara W-4	800965	1058414	1238	1181.4	123.4	56.6
17	BH-30	Dire Jara W-5	801225	1058126	1245	1180.5	156.5	64.5
18	BH-31	Dire Jara W-6	800965	1058414	1240	1180.4	105.5	59.6
19	BH-05	Cement Factory	812378	1061804	1215	1199		16
20	BH-06	Ras Hotel # 2	813870	1061350	1197	1152		45
21	BH-32	Dire Jara W-7	801409	1057966	1247	1179.55	172	67.45
22	BH-33	Dire Jara W-8	801047	1057939	1251	1181.2	187.6	69.8
23	BH-34	Dire Jara W-9	801238	1058620	1315	1262.92	176	52.08
24	BH-35	Dire Jara w-10	801606	1058257	1239	1180.55	150.45	58.45
25	BH-36	Dire Jara W-11	800722	1058418	1239	1181.29	126	57.71
28	BH-39	Dire Jara W-14	801484	1058356	1325	1274.88	154	50.12
29	BH-56	Textile Old W-3	816481	1062864	1191	1165.1	61	25.9
30	BH-57	Textile No. 4	816792	1062510	1189	1161.6	62.5	27.4
31	BH-17	Amdael #2	814239	1064632	1136	1112	124	24
32	BH-18	Cheremiti-1	865002	1079210	1163	1163	70	
33	BH-19	Haseliso	801010	1058803	1264	1235.79	119.4	28.21
34	BH-24	WMERO	814262	1063811	1169	1133.43		35.57
35	BH-25	Jeldesa	842515	1076753	1073	1049.3	90	23.7

36	BH-10	East Afri Bot#2	814020	1061049	1205	1168.5	120	36.5
37	BH-11	East Afri Bot#3	814520	1061049	1205	1168.5	125	36.5
38	BH-71	Sabian TW-6(89)	812052	1064343	1145	1145	122.3	
40	BH-73	Sabian TW-8(89)	812867	1062764	1155	1155	100	
41	BH-74	Sabian TW-9(89)	812461	1064371	1130	1113	129.2	17
42	BH-75	Sabian TW-10(89)	813117	1063444	1160	1139	76	21
43	BH-76	Sabian TW-11(89)	811921	1063785	1150	1139	78	11
44	BH-80	Genderige BH-3	805170	1063115	1150	1138.45	80	11.55
45	BH-91	Hurso mil.camp	788387	1057037	1293.4	1269.56	115	23.84
46	BH-92	Bisrate Gebriel	814120	1063340	1175	1136.5		38.5
47	BH-93	MIN.of Mines	814200	1063530	1192	1161.8		30.2
48	BH-94	Min.of Mines	813010	1061970	1172	1146.58		25.42
49	BH-20	Ras Hotel #1	813883	1061280	1199	1154		45
50	BH-21	High school	813851	1060388	1212	1164	79.2	48
51	BH-22	Dil Chora Hospi	813892	1061139	1210	1170.9	47	39.1
52	BH-23	Dire dawa food cplx	814400	1063426	1170	1137	112	33
53	BH-40	Dire Jara W-15	801425	1058252	1241	1180.44	175	60.56
54	BH-41	Dire Jara W-16	800276	1058325	1236	1181.36	198.5	54.64
55	BH-42	Dire Jara W-17	801738	1058408	1300	1245.37	141.7	54.63
56	BH-43	Sabian Pw-1	812491	1063930	1147	1133.5	72.4	13.5
57	BH-44	Sabian Pw-2	812097	1063961	1144	1134.7	98.8	9.3
58	BH-45	Sabian Pw-3	812511	1063930	1147	1147	55	
59	BH-46	Sabian Pw-4	812527	1063543	1163	1143.3	104.6	19.7
60	BH-47	Sabian Pw-5	812362	1063793	1157	1141.1	101.8	15.9
61	BH-48	Sabian Pw-6	812767	1063462	1174	1151.2	86.2	22.8
62	BH-49	Sabian Pw-7	813081	1063268	1169	1145.3	82.7	23.7
63	BH-50	Sabian Pw-8	812573	1062411	1190	1175	87.7	15
64	BH-51	Sabian Pw-9	813111	1063263	1169	1147.75	71	21.25
65	BH-55	Textile-2(old)	816573	1062781	1195	1176.2	61	18.8
66	BH-53	Elfora	810907	1062360	1210	1187.68	82	22.32
67	BH-77	Bore TW4(2002)	796050	1058100	1165	1133.94	160	31.06
70	BH-95	Prison	814010	1063530	1160	1138.3	47.8	21.7
71	BH-96	Cement factory	815900	1062330	1195	1175.95		19.05
73	BH-98	Airport(erer pr	813060	1064100	1256	1240		16
74	BH-99	Municipality#1	812440	1061310	1192	1166.7	33.5	25.3

75	BH-100	Municipality#2	812460	1060990	1197	1175.1	35	21.9
76	BH-101	Municipality#3	812460	1060990	1195	1184.7	32.5	10.3
77	BH-13	Amdael well #1	814356	1064666	1136	1112	135	24
78	BH-2	Dechatu	816294	1058832	1120	1185		
79	BH-81	MelkaJebdu bh-1	808534	1064055	1140	1140	100	
80	BH-82	Commnd post	811190	1062310	1200	1174		26
81	BH-107	Former Railway	814025	1061390	1212	1174	54.9	38
82	BH-108	Gebremedihn	813700	1060750	1218	1177		41
83	BH-109	Coca Cola(old)	813910	1060990	1217	1187		30
84	BH-83	Genderige BH-5	808532	1063462	1145	1126.32	80	18.68
85	BH-84	Genderige BH-6	805945	1063792	1100	1082	50	18
86	BH-102	Shinile milit.	814072	1065654	1112	1101	119	11
87	BH-103	Russian camp	813531	1061868	1190	1164.2		25.8
88	BH-104	Ejaneni	816386	1058772	1140	1046.5		93.5
89	BH-105	Police training	812730	1061950	1189	1167	65.6	22
90	BH-106	Well drilling c	811900	1061880	1200	1158.9		41.1
91	BH-112	D/D CFE	814091	1061785	1200	1161	54.9	39
95	BH-61	Textile Old W-8	816460	1062460	1195	1150	52.6	45
96	Bh-62	Textile Old W-9	816080	1062886	1174	1135	50	39
97	BH-63	Textile Old W10	816025	1062825	1185	1144	50	41
98	BH-64	Textil Old W-11	816677	1062984	1175	1158	59	17
99	BH-65	Textile O.W-14	816103	1067017	1177	1134.8	78	42.2
100	BH-66	Textile A.W-1	814343	1064427	1133	1095.7	116	37.3
101	BH-67	Textile A.W-2	814652	1064390	1135	1102.87	82.3	32.13
102	BH-68	Textile A.W 3	814531	1064064	1134	1107.58	91	26.42
103	BH-69	Textile A.W. 4	814522	1064772	1192	1156.29		35.71
104	BH-70	Textile N.W 3	816584	1062892	1190	1175.14		14.86
105	BH-85	Cement old BH-2	811170	1062350	1192	1179.2	25	12.8
106	BH-86	High way author	813073	1062031	1190	1159.5	47.2	30.5
107	BH-87	D/D R.R.C.	814072	1064275	1187	1159.5	63	27.5
108	BH-88	Locust control	811806	1062708	1160	1139	48.7	21
109	BH-110	Melka old well	806670	1064100	1320	1300		
110	BH-111	TW5(2002)	809796	1064843	1129	1095.6	124	33.4
111	BH-113	Melkajebdu(old)	806549	1064183	1100	1056.6	125.9	43.4
112	BH-89	Pig farm	810987	1062681	1187	1166.26		20.74

114	DW-14	D/DEdible oil fact.	812941	1061925	1181	1160		
115	DW-20	Jelobelina	815939	1052060	1490	1485		
116	DW-30	Tony farm #1	811769	1063611	1190	1175		
117	DW-31	Christos school	814820	1061283	1236	1200		
118	DW-32	Ras hotel	813690	1061030	1210	1200		
119	DW-17	Pigtry	812380	1062750	1175	1165		
120	DW-33	Lime factory	810820	1062590	1173	1155		
124	DW-37	Abdela Ahmed	814630	1061825	1208	1200		
126	DW-39	Abdurahman hus	815980	1061625	1177	1160		
127	DW-40	She Ismael mosq	815930	1061450	1205	1190		
128	DW-41	Belewa #2	840942	1053804	1230	1220		
129	DW-42	Kanchara #2	810324	1055427	1334	1300		
130	DW-43	Kenchera #3	810150	1055386	1336	1300		
132	DW-02	Garba Anano	857203	1072551	1201	1200		
134	DW-26	Goro(sheh Moham	810773	1062220	1211	1200		
135	DW-27	Goro(Mohamed)	810738	1062334	1200	1185		
136	DW-03	Kalicha	833527	1059032	1590	1580		
137	DW-22	Catholic ch.	816161	1061685	1193	1184		
138	DW-23	ELFORA	811200	1062365	1210	1200		
139	DW-04	Tsehay Hotel	813009	1061596	1179	1160		
140	DW-05	Mudi Anano	819238	1066909	1146	1130		
142	DW-07	Ejaneni	819113	1056268	1388	1375		
143	DW-08	Belewa#1	840894	1058278	1729	1700		
145	DW-10	Bore	798554	1060531	1161	1150		
146	DW-12	Grba Anano	857182	1072675	1197	1180		
148	DW-13	Melka Jebdu	805579	1065086	1114	1100		
149	DW-15	Goladeg	802030	1067013	1091	1075		
151	DW-18	Gende Alo	805943	1064012	1132	1100		
152	DW-19	Gende Rige	806316	1064129	1130	1123		
153	DW-21	Cement Factory	812282	1061937	1180	1175		
154	DW-24	WFP(ABIKIAN)	814317	1063061	1189	1175		
155	DW-28	Tony Farm #3	811366	1063118	1181	1165		
156	DW-29	Tony farm #2	811633	1063807	1173	1165		
157	SP-7	Belewa	842176	1057346		1745		
158	SP-8	Medekedjima	804366	1052194		1501		

159	SP-9	Gende Boru	803501	1050527		1605		
160	SP-10	HARAWATU	803522	1050333		1620		
161	SP11	Borte	800391	1049534		1766		
163	SP-13	Fechase	831945	1055546		1627		
164	SP-14	Cement Factory	812255	1061280		1185		
165	SP-15	Eftua	843185	1054557		1971		
167	SP-1	Legemeda	807621	1053559		1390		
168	SP-2	Halobusa(Legego	810084	1053690		1490		
169	SP-3	Keche	820449	1046854		2027		
171	SP-16	Serkama	845129	1057387		1764		
172	SP-17	Gendesale	835486	1055943		1853		
173	SP-18	Awale Roresa	836775	1052144		1923		
174	SP-19	Bishambaye	830595	1058862		1522		
175	SP-5	Biyoawale	829794	1052057		1881		
176	SP-6	Gende kurto	837595	1057243		1750		
177	SP-20	Harla	819375	1049728		1728		
178	SP-21	Legehare	818219	1061625		1224		
179	SP-22	Mudi Anano	820995	1063252		1393		
180	SP-23	Jarso sp.#1	855079	1049999		2507		
181	SP-24	Jarso-Gendelege	852823	1049830		2470		
182	SP-25	Legedomirga	813438	1048587		1630		
183	SP-26	Jelobelina	817946	1051086		1651		
184	SP-27	Jarso Sebelo	858960	1050555		2480		
186	SP-31	Hulul mojo	799700	1052250		1560		
187	SP-32	Lega bira	821822	1056305		1458		
188	SP-29	Melka(Fuad Haji	805106	1062727		1149		
189	SP.1	Dujuma spring	806900	1053500		1520		
190	Sp-2	Mude Kejama spring	803000	1052000		1620		
191	Sp-3	Bishan mulke spring	802202	1049560		1693		
192	Sp-4	Lega Bira Spring	822500	1055700		1520		
193	SP.5	Fechasa Sp.	828000	1056200		1680		
194	BH-7	Ejianani Hand pump	818000	1056000		1380		
195	BH.8	Shinle town Bh	812000	1072000		940		
196	BH-10	Mermessa Bh	811000	1068100		1060		
197	DW.1	Tsehaye Hotel HD	812963	1061402		1160		

Source EIGS, 1986, Taye A. 1988, DDAC, 2000, WWDSE 2003/2004, E.Abate and MoWR, 2004,